Background Material for SLURP – TOPAZ
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Based on:

- *Manual for the SLURP Hydrological Model Version 12.2*
  Geoff Kite, HydroLogic Solutions (http://www.hydrologic-solutions.com), January 2002.
- *Overview of TOPAZ - an automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation, and subcatchment parameterization*
  Jurgen Garbrecht and Lawrence W. Martz, Rep.# GRL 99-1, Grazinglands Research Laboratory,USDA, Agricultural Research Service, April 1999.

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1. INTRODUCTION

A hydrological model is an attempt to describe the physical processes controlling the transformation of precipitation to runoff and generally includes the hydraulics of water transfer to the ocean or other sink. The detail of the model design will depend on the purpose of the modelling. For simple simulation or forecasting of a streamflow hydrograph, one of the many lumped models will often suffice, but for scientific research it may be necessary to use a more detailed, physically-based, fully-distributed model such as the Système Hydrologique Européen (SHE) model (Abbott *et al.*, 1986).

SLURP (**S**emi-distributed **L**and **U**se-based **R**unoff **P**rocesses) is a conceptual model which, although normally used in semi-distributed form, is capable of use as a fully-distributed hydrological model. The first, 1975, version was developed for use in meso-scale Canadian basins as an alternative to the use of larger and more complicated models such as the U.S. Army Corps of Engineers' SSARR (Streamflow Synthesis and Reservoir Routing) model (Kite, 1975; 1978).

The major advantage of semi-distributed models such as SLURP is that they can incorporate the necessary physics while retaining comparative simplicity of operation. Using SLURP in a semi-distributed form, the model is able to simulate the behaviour of a basin at many points and in many variables while avoiding the data and computation-hungry excesses of the fully-distributed models. In practical applications, the users of both simple lumped models and physically-based fully-distributed models may also tend towards this semi-distributed middle ground. For example, users of lumped models may simulate the use of a distributed model by successively applying a lumped model to sub-basins and, from the other end of the scale, Jain *et al.* (1992) describe the need to use areally-averaged variables in practical applications of the fully-distributed SHE model.

Various concepts have been used in distributed or semi-distributed hydrological modelling to subdivide basins into hydrologically-consistent subareas of the basin.

Leavesley and Stannard (1984) defined a “hydrological response unit” (HRU) as a homogeneous area having a distinct hydrological response and defined by land cover, by soil type, by slope or by aspect. In practice the HRU may be coincident with sub-basins defined by the availability of streamflow gauges. In models for mountain regions the HRU may also be represented by elevation bands (as in the SRM model of Rango, 1995).

The SWIM model (Krysanova *et al.*, 1996) disaggregates a basin into “hydrotops” where a hydrotop is a set of disconnected units in a sub-basin which have a unique land use and soil type. Stuttart *et al.* (1994) used a similar construct in which areas of common land cover are linked. Kouwen *et al.* (1995) described a “grouped response unit” (GRU) for a grid square model in which a GRU is a grouping of all areas with a similar land cover so that a grid square will contain a number of distinct GRUs.

In the SLURP model, the basin is divided into sub-basins on the basis of topography (Figure 1). Each sub-basin is known as an aggregated simulation area (ASA) since it, in turn, is subdivided into sub-areas of different land use. The sub-basin (ASA) used in the SLURP model is therefore similar to a collection of Kouwen's GRUs or Krysanova's hydrotops. It is a grouping of smaller areas each of which has known land cover properties. For example, land cover may be measured from satellite for pixels as small as 10 m but it would be impracticable for a hydrological model to operate at such a pixel dimension for a macro-scale basin. Instead, the pixels are aggregated into areas which are more convenient for modelling.

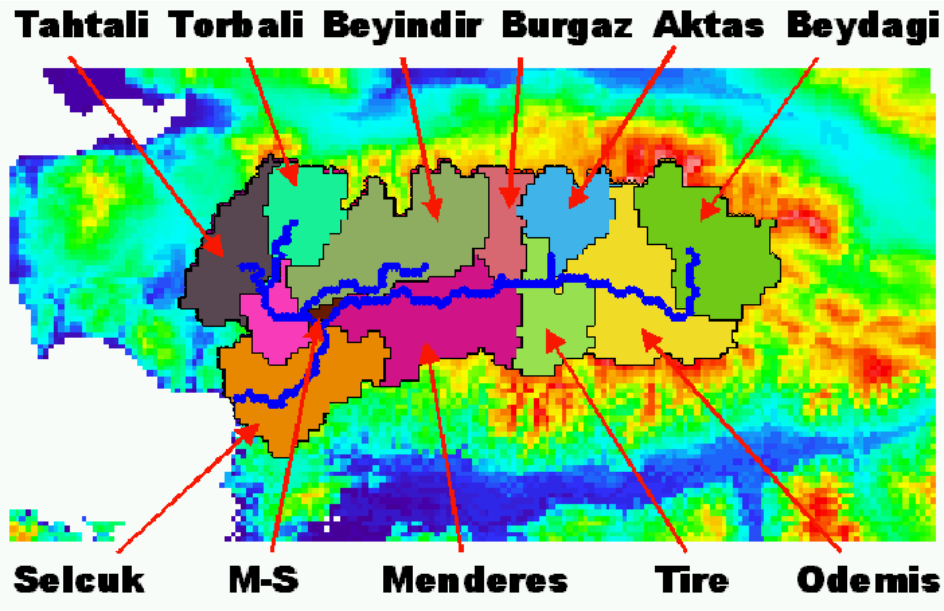

Figure 1: Dividing the basin into sub-basins (ASAs) by topographic analysis.

Although the sub-basins (ASAs) used in the SLURP model could be squares, rectangles or other regularly shaped areas, they are more properly based on stream network shapes derived from the topography since nature does not operate on grid squares. Those models which reduce a basin to a series of grid squares, as in the GRU concept, are attempting to simulate an artificial rather than a natural environment. Hydraulic routing in a grid square model reduces river basins to a series of plates and waterfalls rather like the terraced rice fields of Bali or the Philippines. When we can model quite well the way in which water flows through real rivers and channels there can be no advantage in simulating such an artificial environment. While grid-based hydrological models can usually vary the grid size to some extent; using topographically-based sub-basins (ASAs) allows the size of the sub-basin to vary over the full range of possibilities. A further advantage of modelling the basin with sub-basins (ASAs) rather than a grid is that lakes and reservoirs can be more easily simulated (Kite, 1998).

Land cover data are commonly derived from satellite images and are used in SLURP as an indicator of vegetation type, soil characteristics, and physiography. The very close relationship between land cover and soil characteristics has been demonstrated by Droogers *et al.* (1998). This embedded use of land cover information makes the SLURP model particularly useful for

studies in which land cover is expected to change; for example, in climatic change studies (Kite, 1993). SLURP has the ability to work with land covers that may change any number of times throughout a model run. Figure 2 shows the concept of aggregating land cover data from the pixels of the original map or image into percentages of each land cover for each sub-basin (ASA).

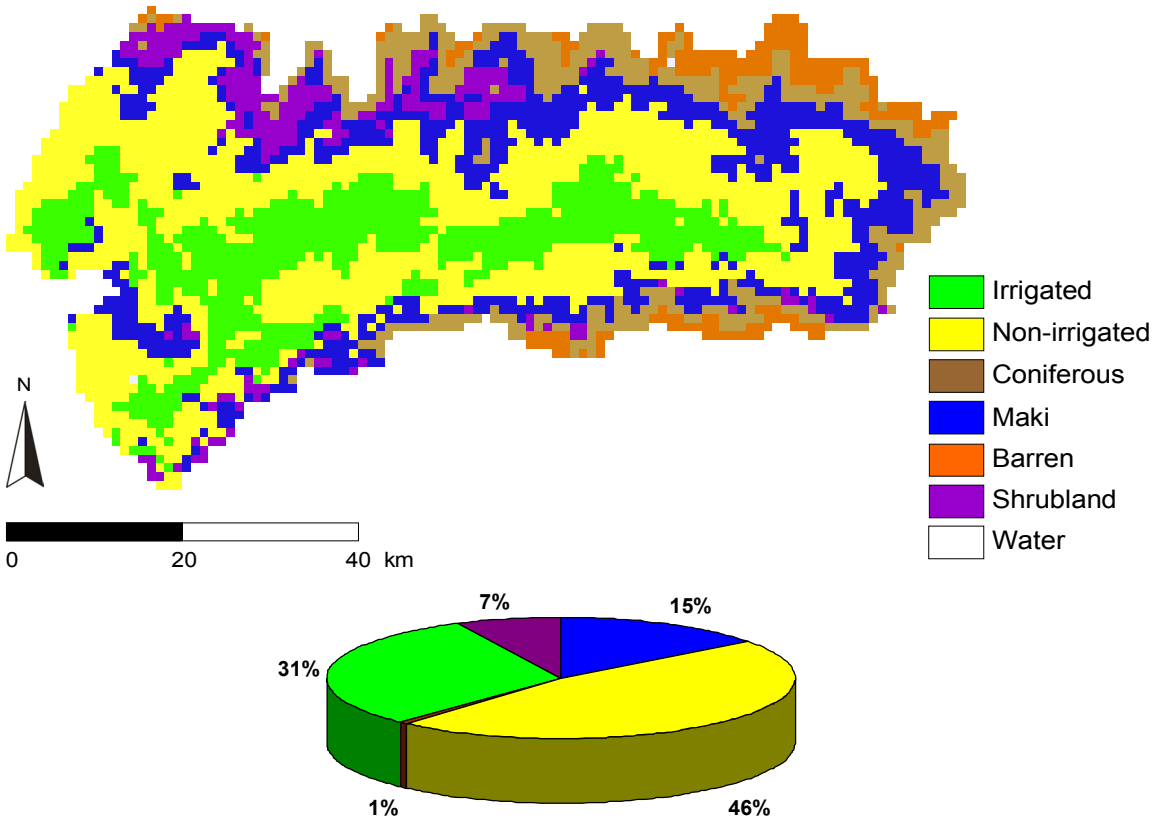

Figure 2: Converting the land cover distribution into percentages for each sub-basin (ASA).

The basic requirements for an ASA are that the distributions of land covers and elevations for elements (pixels) within the ASA are known and that the ASA contributes runoff to a definable stream channel. The latter requirement is also an operational consideration since it means that the stream system within the basin must be at a level of detail such that each ASA contains a defined stream connected to the basin outlet. This is achieved by using digital topographic maps with a stream layer (such as the National Topographic Service 1:50000 and 1:250000 series), by digitizing the stream network as a series of vectors off a topographic map or, preferably, by using an automated delineation of the channel network from digital elevation data with a program such as TOPAZ (Martz and Garbrecht, 1992; Garbrecht and Martz, 1993; Martz and Garbrecht, 1993; Garbrecht and Martz, 1997;Garbrecht and Campbell, 1997). The stream network may then be stored as a vector layer in a geographic information system (GIS) or saved by the topographic analysis package as a file for use in further analyses.

The number of sub-basins (ASAs) used in modelling a basin will depend on the size of the basin and the scales of data available. The SLURP model may use an unlimited number of ASAs and an unlimited number of land covers per ASA, potentially dividing a basin into very many sub-areas. To be sure of stability when calibrating, it is better if the number of ASAs equals or exceeds the number of land cover classes. If the model is to be calibrated, then at least one of the sub-basins (ASAs) must have a streamflow gauge at the outlet.

At each time increment the model is applied sequentially to the matrix of sub-basins (ASAs) and land covers. Each element of the (ASA x land cover) matrix is simulated by four nonlinear reservoirs representing canopy interception, snowpack, a store for fast runoff (may be considered as a combined surface storage and top soil layer) and a store for slow runoff (may be considered as groundwater). The model routes precipitation through the appropriate processes and generates outputs (evaporation, transpiration, surface runoff, interflow and groundwater discharge) and changes in storages (canopy interception, snowpack, fast store and slow store). Runoffs are accumulated from each land cover within a sub-basin (ASA) using a time/contributing area relationship for each land class and the combined runoff is converted to streamflow and routed between each sub-basin (ASA).

A key concept in the development of the SLURP model is that it was designed to make maximum use of remotely sensed data. As well as using land cover information from Landsat or NOAA satellites, the SLURP model may also use NOAA AVHRR visible and infrared data to augment the calculation of snow extent and DMSP satellite data to compute average snow water equivalent over each sub-basin (ASA). This use of satellite data is particularly helpful in applying the model to macro-scale basins where sufficient land-based data may not be available.

Applications of SLURP have been published for basins varying in size from prairie sloughs measured in a few hectares (Su *et al.*, 1997) through small basins of the order of 250 square kilometers (Sabourin, 1996) and basins in the range of 7,500 - 35,000 km^2 (Kite, 1993) to a macroscale basin of 1.8 million square kilometers (Kite *et al.*, 1994) but the model may perform best when applied to meso- and macro-scale basins. Hydrologic models, to be successful, must be able to represent the significant processes at the scale of interest.

The SLURP model allows a choice between five different methods of calculating evaporation from soils and transpiration from vegetation. The first method is the complementary relationship areal evapotranspiration (CRAE) model (Morton, 1983). In most hydrological models and GCMs (e.g. Dickinson & Henderson-Sellers, 1988) actual evapotranspiration is a positive linear function of potential evapotranspiration. In CRAE, on the other hand, the actual evapotranspiration is the complement of potential evapotranspiration; the argument being that a high potential means a low actual and, conversely, a low potential means that the actual evapotranspiration is already high. In a desert there will be a high potential but no actual evapotranspiration. In an irrigated area surrounded by desert there will be a high actual evapotranspiration and a correspondingly low potential evapotranspiration.

The second method for estimating evapotranspiration which is available in the model is also based on a feedback mechanism and takes into account land cover and vegetation (Granger, 1991). This method is adaptable to use remotely sensed data.

The third option is to use the Spittlehouse and Black (S/B) method (Spittlehouse, 1989) which uses the more conventional Priestley and Taylor (1972) method and introduces a soil moisture limited evapotranspiration.

Fourthly, the widely accepted FAO version of Penman-Monteith (Verhoef and Feddes, 1991) is used in the implementation used in the SWAP model (van Dam *et al.*, 1997).

Finally, the Linacre (1977) approximation to the Penman equation is available for data-sparse areas.

In all five methods the overall evapotranspiration from a land cover is computed as evaporation from the canopy and soil surface and transpiration from the vegetation in proportion to the ratio of soil covered and vegetation covered area. The soil and vegetation areas are determined by the leaf area index which may be derived from remotely-sensed data.

In some cases (such as the Great Lakes of the St. Lawrence and Mackenzie Basins) it may be necessary to use the lake evaporation method of Morton *et al.* (1985) which accounts for seasonal changes in sub-surface heat storage to simulate the lag between air temperature and evaporation.

Table 1: Comparison of evapotranspiration methods

Method	**Advantage**	**Disadvantage**
Penman-Monteith	Widely accepted	Data intensive
Priestley-Taylor	Separate E and T	Uses coefficients
Morton CRAE	Better logic	Not widely accepted
Granger	Uses satellite data	Data intensive
Linacre	Uses only temperature data	Approximation only

2. DESCRIPTION OF THE SLURP MODEL

2.1 The Vertical Water Budget

2.1.1 Evapotranspiration

At a particular time step, the first operation within the vertical water balance for a particular land cover and sub-basin (ASA) is to compute the evapotranspirative demand. As noted earlier, potential evapotranspiration may be computed in any of five different ways:

a) Using the complementary relationship areal evaporation model (CRAE) (Morton, 1983). CRAE computes a potential evapotranspiration by solving the energy balance and aerodynamic equations at equilibrium temperature using a modification of the Penman (1948) equation in which the wind function is replaced with a vapour transfer coefficient. Daily net radiation is computed from either recorded hours of bright sunshine or recorded global radiation. A wet-environment evapotranspiration is computed from the slope of the saturation vapour pressure/temperature curve and the net radiation. The actual areal evapotranspiration is then computed as the difference between twice the potential and the wet evapotranspiration.

b) With the Granger (1995) method which uses surface temperature in a feedback relationship with vapour deficit. In this method, surface temperature may be obtained from remotely sensed data. A net radiation algorithm may also use data from channel 1 of the NOAA advanced very high resolution radiometer (AVHRR) as an indicator of albedo. Daily evapotranspiration at each 1 km pixel is computed from net radiation and vapour pressure deficit and averaged over each type of land cover. Daily wind data are optional with this method.

c) Using the Spittlehouse (1989) technique in which available energy is calculated using the Priestley and Taylor (1972) approach and the available soil moisture is calculated as a function of the field capacity and root zone depth. Evaporation from the canopy interception and the soil, and transpiration from the vegetation, are computed separately in this method.

d) Using the FAO version of the Penman-Monteith (Verhoef and Feddes, 1991) algorithm. In SLURP, a version of the implementation in the SWAP model (van Dam, *et al.*, 1997) is used. This implementation computes bare soil and dry crop potential evapotranspiration and requires information on crop height and canopy resistance. Daily wind data are required for this option.

e) Using the Linacre (1977) approximation to the Penman equation. This method uses only temperature data. Clemence and Schultze (1982) found that the Linacre method performed better than other temperature-based methods. The version used in SLURP includes the daylight hours correction factor proposed by Dent *et al.* (1988).

The Morton method has the advantage of not requiring many parameters but it does not take into account the properties of different land cover types. The Granger method takes into account vegetation type and requires either wind data or a windspeed function. The Spittlehouse method computes transpiration and evaporation separately and requires three extra parameters for each land cover type. It is well known that the Priestley-Taylor algorithm (on which Spittlehouse is based) underestimates potential evapotranspiration in arid and semi-arid environments. A critical review of the Morton, Granger and Spittlehouse methods is given in Barr *et al.* (1997). The implementation of the Penman-Monteith method is the most data intensive but has the advantage of being the FAO standard. For most purposes, and particularly if irrigation is included in the basin, the Penman-Monteith method is the most appropriate as it allows differentiation by crop.

For each of the first four methods, SLURP may use either hours of bright sunshine (or the ratio of recorded hours of sunshine to the maximum possible hours of sunshine) or global radiation as input. When sunshine data are used as input, the ASA-average daily global radiation in MJ/m^2/day will be computed by SLURP and written to file and may be used in subsequent model runs.

Vörösmarty *et al.*, 1998, have noted in a comparison of eleven evapotranspiration methods, that errors in simulating streamflow were caused much more by problems with precipitation and snowmelt than by differences in estimation of potential evapotranspiration.

For all methods except Linacre, the net radiation is computed within the model from recorded global radiation or from recorded hours of bright sunshine and computed extraterrestrial radiation as follows:

- The direct beam clear sky radiation (Q_{dro}) is calculated (Granger and Gray, 1990) from:

$$Q_{dro} = \frac{I_o}{r^2} \int p^M \cos(X\Lambda S) dh \qquad (1)$$

  where I_o is a solar constant (1.35 kW/m^2), r is the radius vector of earth's orbit, p is the mean transmissivity of the atmosphere along the zenith path, M is the optical air mass, cos(XΛS) is the cosine of the angle of incidence of the sun's rays on the surface, and h is the hour angle of the sun. The integral is taken over the duration of sunlight. In the Penman-Monteith method, direct beam clear sky radiation (Q_{dro}) is computed using a simpler approximation.

- Incoming radiation is then reduced to account for cloud cover (Q_{drs}) using

$$\frac{Q_{drs}}{Q_{dro}} = 0.024 + 0.974\left(\frac{n}{N}\right)1.35 \qquad (2)$$

  where n is the actual number of hours of bright sunshine in the day and N is the maximum possible number of hours of bright sunshine in the day.

- The clear sky diffuse radiation (Q_{dfo}) is obtained from:

$$Q_{dfo} = 3.5(\frac{P}{P_0})\cos(X\Lambda S) + 0.45\sin(\frac{2\pi \cdot (172 - day}{365}) \quad (3)$$

where P is the pressure at the surface, P_0 is the standard pressure at sea level, day is the Julian day of the year, and the rest of the variables are the same as for Equation 1.

- The diffuse radiation is then increased due to cloud cover as:

$$\frac{Q_{dfs}}{Q_{dfo}} = 2.68 + 2.2(n/N) - 3.85(n/N^2) \quad (4)$$

- The total global shortwave radiation is the sum of the direct (Q_{drs}) and diffuse (Q_{dfs}) radiation. The net shortwave radiation is then found by taking into account surface albedo. Net shortwave radiation (Q_s) is finally:

$$Q_s = Q_{drs} + Q_{dfs}(1 - \alpha) \quad (5)$$

where alpha is the surface albedo.

- Outgoing net longwave radiation (Q_{ln}) is then obtained using

$$Q_{ln} = \sigma T_a^4 (0.34 - 0.139\sqrt{e_a})(0.1 + 0.9(\frac{n}{N})) \quad (6)$$

(Verhoef and Feddes (1991), where T_a is the absolute temperature in degrees Kelvin, e_a is the vapour pressure in kPa, and σ is the Stefan-Boltzmann constant. The net radiation available for evapotranspiration, Q_n is Q_s - Q_{ln}.

- Maximum soil heat flux, G, in MJ/m^2/day and the date on which this occurs is specified by the user and SLURP then computes the soil heat flux for a particular day using a sine curve. Soil heat flux is positive when the soil is warming and subtracted from net radiation. Soil heat flux for a month may be estimated as (Allen *et al.*, 1998):

$$G = 0.14(T_{monthi} - T_{monthi-1})$$

where T_{month} is the mean monthly air temperature. In many cases soil heat flux is small and may be ignored.

Potential evapotranspiration is computed from the net radiation differently by each method.

Computing Potential Evapotranspiration using the Morton CRAE Method

Areal evapotranspiration is calculated over an entire sub-basin (ASA) from potential and wet environment evaporation and is taken first from the canopy, then the snowpack (if it exists), then from the fast store and finally from the slow store.

More conventional evaporation models (such as the Spittlehouse/Black described below) compute a point potential evapotranspiration E_p using the Penman (1948) or similar method and then calculate a point 'actual' evapotranspiration E_a as a positive linear function of the potential:

$$E_a = \alpha E_p \tag{7}$$

where α is an arbitrary coefficient. A variation on this method replaces α with resistance factors such as those of Monteith (1981).

The CRAE model, however, first computes an areal wet-environment evaporation E_w and then calculates the areal 'actual' evapotranspiration E_a as a complementary function of the wet-environment value (Bouchet, 1963):

$$E_a = 2E_w - E_p \tag{8}$$

The CRAE model computes E_p by solving the energy balance and aerodynamic equations at equilibrium temperature using a modification of the Penman equation to replace the wind function with a vapour transfer coefficient. E_w is computed from an empirical equation using the slope of the saturation vapour pressure/temperature curve and global radiation. The version of the CRAE model built into SLURP uses mean daily temperature, dew-point temperature and either hours of bright sunshine, the ratio of actual hours to theoretical sunshine hours or global radiation.

Figure 3 shows the relationships between E_a, E_w and E_p. The abscissa represents water supply and the ordinate indicates the magnitude of the various evaporation terms. The left hand side of the diagram shows that with no water supply there can be no actual evaporation, resulting in a very high potential evaporation. Moving to the right along the x-axis, as the water supply increases, the actual evaporation increases and the potential evaporation decreases until, when the water supply reaches its limiting value, both values meet at the wet-environment evaporation.

In the SLURP model, the CRAE areal potential evapotranspiration, E_a, is divided into a soil evaporation demand, *e_soil*, and a crop transpiration demand, *e_water*, using the relative areas of soil and vegetation cover within a given land cover as:

$$\begin{aligned} e\_soil &= E_a \times soil\,cover \\ e\_water &= E_a \times crop\,cover \end{aligned} \tag{9}$$

$$e_{actual} = e_{potential} \times \frac{store - \max \times w_p}{\max \times \left(f_c - w_p\right)} \tag{10}$$

where *soilcover* and *cropcover* are fractions of total cover as computed from LAI in Equation 22. The actual evaporation and transpiration are limited by the relationship of the current fast or slow store contents, *store*, the soil field capacity, f_c, and the wilting point, w_p. In SLURP, the field capacity and wilting point are input as decimals of the maximum water capacity, *max*, of the fast and slow stores and are converted to mm in the program.

The field capacity is defined as the soil water content reached when water has been allowed to percolate naturally from the soil until drainage ceases and the remaining water is held by capillary forces great enough to resist gravity. The (permanent) wilting point is the lower limit of soil water available to plants. At the wilting point, the hydraulic conductivity is so low that water cannot move to the roots and no water is available for transpiration. Field capacity, wilting point and porosity may be estimated from soil types using pedo-transfer functions.

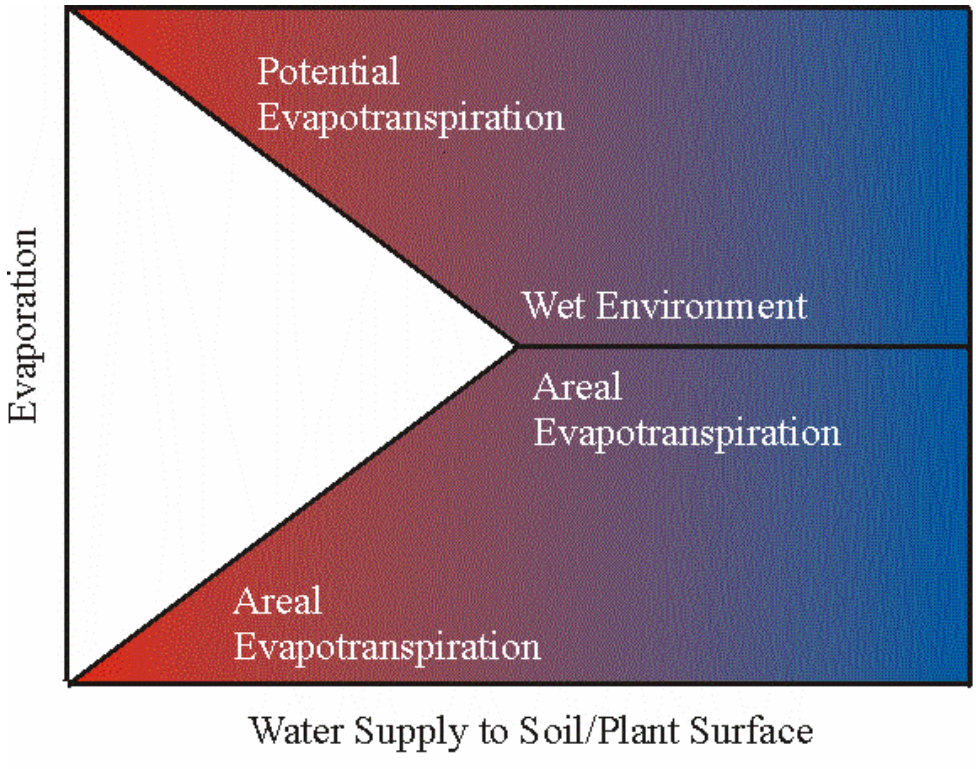

Figure 3: Relationship between actual, potential and wet-environment evaporations in the CRAE model (Morton, 1983).

Computing Potential Evapotranspiration using the Granger Method

Evapotranspiration E (mm) is calculated for each land cover as:

$$E = \frac{\nabla G O_N + \gamma G E_a}{\nabla G + \gamma} \tag{11}$$

where ∇ is the slope of the vapour pressure curve (kPa/ºC), G is the relative evaporation (dimensionless), Q_N is the net radiation (mm eq./d), γ is the psychrometric constant (0.066 kPa/ºC) and E_a is the drying power (mm eq./d).

G is computed from D, the relative drying power (dimensionless) which, in turn, is derived from:

$$G = \frac{1}{0.905 + 0.095 e^{6.2D}} + 0.2(1 - D)$$

E_a, the drying power (mm eq./d), f_u, a wind speed function (mm/d kPa), e_a, the vapour pressure (kPa) and e_a^*, the saturated vapour pressure at the air temperature (kPa).

$$D = \frac{E_a}{E_a + Q_N}$$

$$E_a = f_u (e^*_a - e_a)$$

The wind speed function f_u is defined as:

$$f_u = a + b \cdot U$$
$$a = 8.19 + 0.22 Z_0$$
$$b = 1.16 + 0.08 Z_0$$

where U is the wind speed (m/s) and Z_0 is an aerodynamic resistance (s/m) for the particular land cover.

In SLURP two options are available for Granger evaporation. If daily average wind speed (m/s) data are available then an aerodynamic resistance Z_0 is input for each land cover in the Granger Feedback Evapotranspiration data input window. If wind data are not available, then the input window is used to input the wind speed function f_u directly. Z_0 usually varies between 30 for grass and 150 for trees (Allen et. al., 1989) and f_u is between 10 and 30. If the mean daily wind speed is used, then this will be multiplied by 1.33 to obtain the average daytime wind speed (Smith, 1992).

The Granger potential evapotranspiration, E_a, is divided into a soil evaporation demand, *e_soil*, and a crop transpiration demand, *e_water*, using Equation 9 and the actual evaporation and transpiration are limited by the relationship of the current fast or slow store contents, *store*, the soil field capacity, f_c, and the wilting point, w_p using Equation 10.

Computing Potential Evapotranspiration using the Spittlehouse/Black Method

The Spittlehouse/Black (Spittlehouse, 1989) method of computing evapotranspiration uses the Priestley and Taylor (1972) equation for water and soil separately:

$$e\_water = \alpha_{water} \times \frac{s}{s+\gamma} \times (R_n - G)$$

$$e\_soil = \alpha_{soil} \times \frac{s}{s+\gamma} \times (R_n - G) \qquad (12)$$

$$e\_swl = \beta \times \frac{store - \max \times wilt}{\max \times (field - wilt)}$$

where *e_water* and *e_soi*l are the energy limited evapotranspiration rates (mm) from water and soil respectively, α is the empirical Priestley-Taylor coefficient, s is the slope of the saturation vapour pressure curve (kPa/ºC),. γ is the psychrometric constant 0.066 kPa/ºC, R_n is the net radiation and *G* is the soil heat flux. Barr *et al.* (1997) found that α varies from 1.26 for crop or grass to 0.80 for coniferous forest. Shuttleworth (1993) recommends α =1.26 if relative humidity exceeds 60% and α =1.74 otherwise.

e_swl is the soil water limited transpiration rate (mm) and β is an empirical coefficient. Spittlehouse (1989) recommended estimating β using the assumption that soil moisture begins to limit evapotranspiration at about 30% extractable soil moisture and E/α = 4.0 mm/day. This assumption may be expressed as β/α = 13 mm/day and gives values of β of 10 mm/day for coniferous forest and 16 mm/day for pasture.

Store and max are the current and maximum possible soil water contents (mm) and *field* and *wilt* are the field capacity and wilting point as decimals (0.0 - 1.0). The average evapotranspiration demand from the Spittlehouse/Black method for the whole land cover is determined from the relative areas of soil and crop cover.

The Spittlehouse/Black method requires air temperature and soil heat flux for each ASA. For each land cover it also requires the coefficients alpha and beta, the field capacity and the wilting point. The underlying Priestley-Taylor relationship has been found (Verhoef and Feddes, 1991) to slightly underestimate in the low evapotranspiration range (< 2 mm/day) and to seriously underestimate in semi-arid and arid regions where evapotranspiration exceeds 6 mm/day.

Computing Potential Evapotranspiration using the FAO Penman-Monteith Method

The FAO combination method was developed (Verhoef and Feddes, 1991) from the Penman-Monteith algorithm:

$$E_p = \frac{s}{s+\gamma} \times \left(R_n - G\right) + \frac{\lambda}{s+\lambda} \times U_2 \times \left(e_a - e_d\right) \qquad (13)$$

where E_p is the potential evapotranspiration, s is the slope of the vapour pressure curve, γ is the adiabatic psychrometric constant, R_n is the net radiation, G is the soil heat flux, U_2 is the windspeed at 2 meters and e_a - e_d is the vapour pressure deficit with e_a as the saturation vapour pressure and e_d as the saturation vapour pressure at dewpoint.

In the SWAP version (van Dam *et al.*, 1997) of the FAO combination method used in SLURP the radiation term uses separate albedos for crop and soil (further modified in SLURP for ageing snowpack) and the aerodynamic resistance depends on the crop height and canopy resistance.

The crop height on a particular day is computed in SLURP from the maximum crop height and the stage of plant growth. The start and end of the growing season are specified on an input screen and stored in file <command_name>.pm. For land covers such as forests and shrubs the growing season is year-round.

Computing Potential Evapotranspiration using the Linacre Method

The Linacre (1977) pan equivalent potential evaporation in mm/day is computed as (Schultze, 1989) as:

$$E = \frac{700T_m/(100-\phi) + u(T_a - T_d)}{80 - T_a} \qquad (14)$$

where $T_m = T_a + 0.006\, A_m$, *and* T_a is the mean air temperature, A_m is the elevation (m), ϕ is the latitude in degrees, u is a wind factor (often defaulted to 15) and $T_a - T_d$ is the difference between air and dewpoint temperatures approximated by:

$$T_a - T_d = 0.0023\, A_m + 0.37\, T_a + 0.53\, R_m + 0.35\, R_{hc} - 10.9$$

with R_m *as* the mean daily or monthly range in temperature and R_{hc} as the difference between the mean temperatures of the hottest and coldest months of the year.

Dent *et al.* (1988) adjusted equation 14 by adding a correction for the length of daylight to:

$$E = \frac{D.700T_m/(100-\phi) + u(T_a - T_d)}{80 - T_a}$$

where D is the number of daylight hours divided by 12.

Computing Actual Evapotranspiration from Potential

For all five methods the soil evaporation and crop transpiration are computed and recorded separately in the SLURP model depending on the daily ratio of soil and crop cover within each land cover. The ratio of actual to potential evaporation and transpiration varies with the current contents of the soil water stores. If the current content is greater than the field capacity of the soil then the ratio varies from 0.3 to 1.0. If the current content is between the field capacity and a point (f) half way between the field capacity and the wilting point then the ratio is 1.0. If the current content is between f and the wilting point, then the ratio varies from 1.0 to 0.0. Finally, if the current content is less than the wilting point, then the ratio is 0.0.

2.1.2 The Vertical Water Balance for all Land Covers except "Water"

Figure 4 shows a simplified flow chart of the vertical water balance that the SLURP model applies to each element of the matrix of ASAs and land covers (except for a water "land cover"). The structure contains four non-linear reservoirs or stores, one for canopy storage, one for snowpack, one for a rapid runoff (may be considered as a combined surface storage and top soil layer storage) and one for a slow runoff (may be considered as a groundwater response). Model parameters include the initial contents of snow storage (mm), the initial water content of the slow store, as a percent of the maximum capacity and a maximum infiltration capacity (mm/day). There are retention constants and maximum capacities for both the fast store and the slow store.

The vertical water balance operates at a daily time step. The sequence of operations is as follows:

- The daily precipitation (mm) for an ASA is adjusted to the mean elevation of the land cover using an estimated percent change per 100 m in two stages. First during the process of deriving ASA-average precipitation from climate station data and, second, when converting from ASA-average precipitation to land cover precipitation in the daily water balance. There is a cap on the maximum percent increase in precipitation of 50% at both stages. Because each land cover occupies a band of elevation there is also a precipitation correction factor. This should normally be set to 1.0 but may be used to compensate for known gauge undercatch.

  One of the biggest problems facing hydrological modellers is that of obtaining distributed precipitation data. Without good distributed precipitation data, the most physically-sophisticated distributed model will give no better results than the simplest lumped model. The vertical water balance in SLURP assumes that each sub-basin (ASA) either has precipitation data derived from an (external) distribution scheme such as radar or an atmospheric model or uses Thiessen weights and lapse rates in Option 4 to distribute data from climate stations. Optionally, the precipitation data may be modified by the percentage of the ASA covered by cloud, as derived from NOAA AVHRR visible and near infrared satellite data (Kite, 1989a).

- Precipitation is intercepted by the vegetation canopy. The maximum canopy capacity is set as the product of the canopy capacity and the leaf area index (LAI). The canopy capacity is filled by intercepted precipitation as (Spittlehouse, 1989):

$$I = AP^{B} \qquad (15)$$

where P is the precipitation (mm), I is the interception (mm) and A and B are coefficients. There are other models for interception, e.g. Calder (1996), which take into account drop size and multiple canopy layers but since, in most cases, evaporation from interception is relatively small, the above equation seems adequate.

The model initially sets A to $1/LAI_{max}$ and sets B to 1.0 so that interception is proportional to the ratio of actual LAI to maximum LAI. The user may reset these initial settings. Interception is limited by the maximum canopy capacity. The model interpolates daily values of LAI from beginning-of-month values.

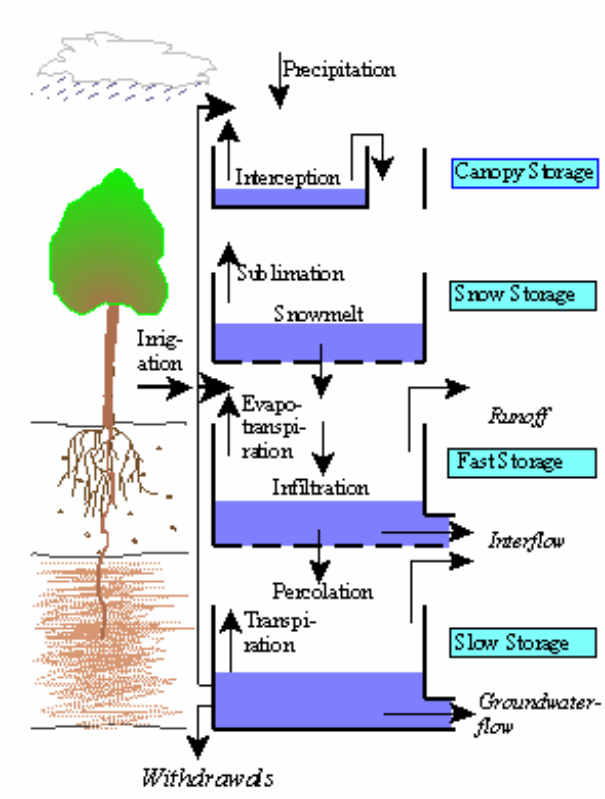

Figure 4: Simplified flow chart of the vertical water balance applied to each land class within each sub-basin (ASA).

Intercepted water is evaporated from the canopy at rate e_water.

Land cover albedo is input by the user. In the Penman-Monteith method, soil albedo is assumed to be 0.15 and canopy resistance is set to 0. Canopy resistance for other crops varies between 30 s/m for arable crops to 150 s/m for forest (van Dam *et al.*, 1997). These parameters are not used in the Morton, Granger or Spittlehouse methods.

- The mean daily air temperatures, TºC, are derived for each land cover in each sub-basin (ASA) by adjusting for elevation using a vertical lapse rate in two stages. First during the process of deriving ASA-average temperatures from recorded and, second, when converting from ASA-average temperatures to land cover temperatures. If the mean air temperature for the land cover is above a critical temperature, then the precipitation is assumed to be rainfall. The critical temperature should be set initially to 0.0 but, as average lapse rates are used and as any particular land cover is not all at the same elevation, some minor adjustment above or below 0.0 may be necessary. Setting the critical temperature to a small positive value will increase the percentage of precipitation which occurs as snow. Dew point temperatures are lapsed at a rate of 20% that used for air temperature.

- Rainfall left over from the canopy is added to the fast store.

- A second store represents snow storage. If the daily mean temperature is below or equal to the critical temperature then precipitation is assumed to be snowfall and is accumulated to the snowpack S_P. If the temperature is above the critical temperature, precipitation is assumed to be rain.

  Land cover albedos can be adjusted for the effects of snow on the land cover. The snowpack albedo is set to 0.80 initially and reduced as:

$$a_i = 0.086 + 0.798.a_{i-1} \tag{16}$$

  each day to a minimum of 0.40 or until the snowpack is melted or sublimated. If fresh snow falls, the albedo is reset to 0.80 (US Army, 1966).

  The snowpack may then be depleted by snowmelt, S_m. This may be done in two ways in SLURP.

  First, a simple degree-day approach may be used in which melt depends only on a melt rate, R_1 mm/day/ºC, and the temperature in degrees above the critical temperature, T_{crit}:

$$S_m = R_1(T - T_{crit}) \tag{17}$$

  In SLURP, the snowmelt rate R_1 on any day is calculated using a parabolic interpolation from values specified for each land cover on January 1st and July 1st. WMO (1974) provides some estimates of the range of melt rates (Table 2)

Table 2: Some typical values of snowmelt rates.

Month	Forested	Non-forested
April	2.0	4.0
May	3.0	6.0
June	4.0	7.0

Many studies (e.g. Tarboten *et al.*, 1991; Vehviläinen, 1991; Rango and Martinec, 1995) have found that, despite its simplicity, the degree-day method of snowmelt is not easily improved upon, even by a full energy balance approach.

Second, SLURP may use the simplified energy budget method proposed by Kustas *et al.* (1994). Brubaker *et al.* (1996) describe the application of this "restricted degree-day" algorithm to the Snowmelt Runoff Model (SRM) (Martinec *et al.* 1994). In this algorithm, the melt rate is a constant (different for each land cover in SLURP) and does not vary with season. The increased melting later in the season is simulated using net radiation data so that Equation 17 becomes:

$$S_m = R_2 (T - T_{crit}) + \alpha \, Q_n \qquad (18)$$

where R_2 is the restricted degree-day snowmelt rate, Q_n is the net radiation in MJ/m^2/day and α is a conversion factor. Brubaker *et al.* (1996) used a value of 2.0 mm/day/ºC for R_2 . The theoretical value of α, the radiation conversion factor, is (Allen *et al.*, 1998) the inverse of the latent heat of vapourization, i.e. 0.408 mm per MJ/m^2 which is equivalent to 0.035 mm per W/m^2.

Pietroniro *et al.* (1997) compared the simple degree-day and the restricted degree approaches for a northern basin and found that the addition of radiation data made no significant difference. The snowmelt rates and conversion factors calibrated in their model are given in Table 3.

In the implementation of this method in SLURP a different value of α is used for each land cover to allow for the different proportion of radiation intercepted by the various heights of vegetation. When SLURP is run with either hours of bright sunshine or global radiation, the net radiation needed for snowmelt will be computed internally.

Climate change scenarios, such as those generated by GCMs for increased atmospheric greenhouse gases, change not only air temperatures but also cloud cover, and hence net radiation. If SLURP is used to evaluate the effects of such a climate change scenario on hydrology and water resources, the advantage of the restricted degree-day approach is that it can include separate changes for temperature and net radiation.

Table 3: Values of snowmelt rates and radiation conversion factors, Pietroniro *et al.* (1997)

Land cover	Degree-day melt rate mm/day/°C	Restricted degree-day melt rate mm/day/°C	Radiation conversion factor mm/w/m^2/day
Deciduous/mixed forest	1.80	0.12	0.27
Coniferous forest	1.80	0.84	0.17
Transitional forest	3.36	1.08	0.28
Open wetlands	2.88	0.84	0.31

Snowpack, in terms of snow water equivalent (SWE), may also be input directly to the model from snowcourse data or computed from passive microwave data (Slough & Kite, 1992). It was found that for a mountain basin, data from individual snowcourses are of little or no use in the model: point SWE measurements are not good estimates of ASA averages. SWE values computed from passive microwave data, on the other hand, provide better estimates because they themselves are average values from large areas (e.g. 25 km x 25 km for data from the DMSP satellite for south-eastern British Columbia). In addition, the microwave data are available in all weathers and at frequent sampling intervals. Snowmelt may, optionally, be modified by the areal extent of snowcover from NOAA AVHRR images (Kite, 1989a).

- The subsurface flow processes are simulated using two linear reservoirs, the fast store, which may be considered as an unsaturated soil layer contributing surface runoff, interflow and percolation to a deeper slow store and allowing soil evaporation and crop transpiration. The slow store is a source of interflow, groundwater flow and transpiration (Figure 4).

  Rainfall and any snowmelt infiltrates through the soil surface into the fast store depending on the current infiltration rate:

$$Inf = (1 - \frac{S_1}{S_{1,\max}}) * Inf_{\max} \qquad (19)$$

  where S_1 is the current contents of the fast store, $S_{1,max}$ is the maximum capacity of the store and Inf_{max} is the maximum possible infiltration rate. If the water supply is higher than Inf or the fast store is full, the water excess is spilt as surface runoff, RO.

  Since the model operates on a daily time step it is difficult to include any better representation of the physics of infiltration. Other authors (e.g. Krysanova *et al.*, 1996) divided daily rainfall into 4 mm slugs which allowed use of a smaller infiltration rate but this is equally artificial. Still other models use various approximations to the Richardson equation (Richards, 1931) but this is not suitable for a daily time step. Previous versions of SLURP

(Kite, 1995) used the Philip (1954) refinement of the early Green & Ampt (1911) equation based on Darcy's equation for flow in porous media but, again, this was found to be ineffective at the model's daily time interval.

If the current content of the fast store, S_1, is higher than the field capacity, FC, then the excess is spilled as interflow, RI.

Percolation from the fast store to the slow store takes place at a rate depending on the current store contents, S_1, the wilting point, WP and the retention constant, k_1:

$$PERC = (S1 - WP) / k_1 \tag{20}$$

Evaporation and transpiration are taken from the fast store in proportion to the percentages of soil and vegetation cover derived from the LAI (Vanclooster *et al.*, 1994):

$$E = \text{soilcover} \cdot E_{soil} + \text{cropcover} \cdot E_{water} \tag{21}$$

where

$$soilcover = \text{e}^{-0.6\,LAI} \tag{22}$$

- The percolation is added to the slow store which then generates groundwater flow (RG) as:

$$RG = \frac{1}{k_s} * S_2 \tag{23}$$

where k_2 is the slow store retention constant and S_2 is the current contents of the slow store. If overflow from the slow store occurs it will be added to the interflow component RI.

- Transpiration is extracted from the slow store.

The concepts used in the vertical water balance are simple and use parameters which may be readily estimated. Many studies (e.g. Naef, 1981; Jain *et al.*, 1992; Grayson *et al.*, 1992a, Grayson *et al.*, 1992b; Jakeman and Hornberger, 1993) have demonstrated that the use of more sophisticated models making use of field and laboratory measurements of infiltration and groundwater parameters does not provide improved results.

2.1.3 Vertical Water Balance for a "Water" Land Cover

SLURP can handle a water "land cover" within a sub-basin (ASA) in two different ways. If the water is a lake or reservoir for which regulation or routing is specified (on Figure 5) then the vertical water balance for the water within the ASA will be carried out as part of the regulation or routing as described in section 2.3.3.

If, on the other hand, the water in an ASA represents only a small unregulated lake or even a collection of small water bodies then the vertical water balance is carried out as for any other land cover except that some of the parameters are changed to eliminate the functions of the canopy store and the fast store and to ensure that evapotranspiration from the slow store is assigned to evaporation and not transpiration. For a water "land cover", the parameters and associated variables should be set as follows:

LAI - set to 0.0
canopy capacity - set to 0.0
interception coefficients - set to 0.0
wilting point - set to 0.0
field capacity - set to 1.0
porosity – set to 1.0
max. crop height set to 0.0
start and end of crop growing season set to 0

Parameter 1 - Initial contents of snow store (mm) - set as normal
Parameter 2 - Initial contents of slow store (%) - set to 50%
Parameter 3 - Maximum infiltration rate (mm/day) - set to maximum
Parameter 4 - Manning roughness, n - set to 0.0
Parameter 5 - Retention constant for fast store - set to 1.0
Parameter 6 - Maximum capacity for fast store (mm) - set to 0.0
Parameter 7 - Retention constant for slow store - set to maximum
Parameter 8 - Maximum capacity for slow store (mm) - set as estimated maximum lake depth
Parameter 9 - Precipitation factor - set to 1.0
Parameter 10 - Rain/snow division temperature (deg C) - set to 0.0

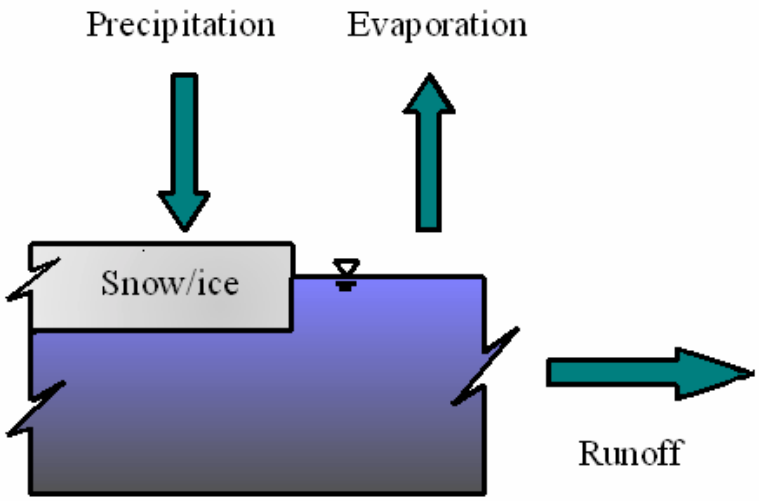

Figure 5: Simplified flow chart of the vertical water balance applied to a water 'land cover'.

2.2 Routing within a Sub-basin (ASA)

Runoff from each land cover is first routed to the nearest point on a stream and then routed down the stream to the sub-basin (ASA) outlet. In a fully distributed model this routing would be done for each cell or pixel of the basin. In the semi-distributed approach taken in SLURP we compute the distances for each pixel and then calculate the moments of normal distributions fitted to the to-stream and down-stream distances. Figure 6 shows this concept and Figure 7 gives an example of the distributions of these distances for land classes used in one ASA of the Küçük Menderes Basin.

The statistics required are the mean and standard deviation of the distances to the nearest stream for each land cover, the mean and standard deviation of the distances along the stream to the ASA outlet for each land cover and the average changes in elevation to the nearest stream and down the stream for each land cover.

To compute travel times for each land cover it is necessary to estimate a velocity for travel to-stream and a velocity for travel down-stream. Naden (1993) used a velocity of 0.6 m/s for networks of the order of 10,000 km² and Wyss *et al.* (1990) used a subsurface velocity of 2×10^{-3} m/s and a channel velocity of 0.6 m/s for small New England catchments. SLURP computes an average velocity, V m/s, for each land cover for flow to the stream using Manning's equation with a different coefficient of roughness for each land cover, n, and assuming that the hydraulic radius, R, is a small number for wide shallow flow. If H is the average change in elevation over the distance, L, to the stream, then

$$V = (1.00/n)R^{2/3}(H/L)^{1/2} \tag{25}$$

Representative minimum and maximum distances to-stream are computed from the mean (μ) and standard deviation (σ) as

$$\begin{aligned} L_{\min} &= \mu - 2\sigma \\ L_{\max} &= \mu + 2\sigma \end{aligned} \tag{26}$$

The minimum and maximum to-stream travel times are then computed for each land cover using the velocity from Equation 25 and the minimum and maximum distances from Equation 26.

Similarly, Manning's equation is used with measured stream depth, width and estimated stream roughness to calculate a stream velocity.

Travel time down-the stream to the ASA outlet for each land cover is computed from the mean distance down-stream, the change in elevation down-stream, and the stream-velocity.

Total travel times are the sums of the to-stream and the down-stream travel times.

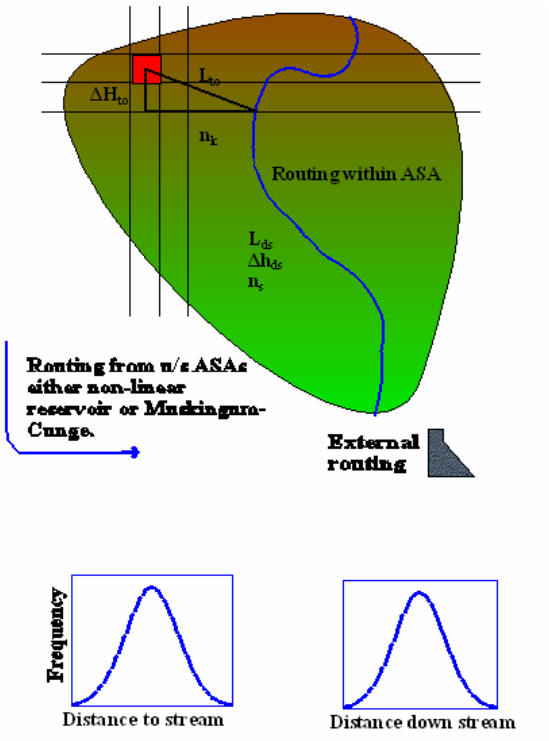

Figure 6: Concept of within-ASA routing using distributions of to-stream and down-stream distances for each land cover.

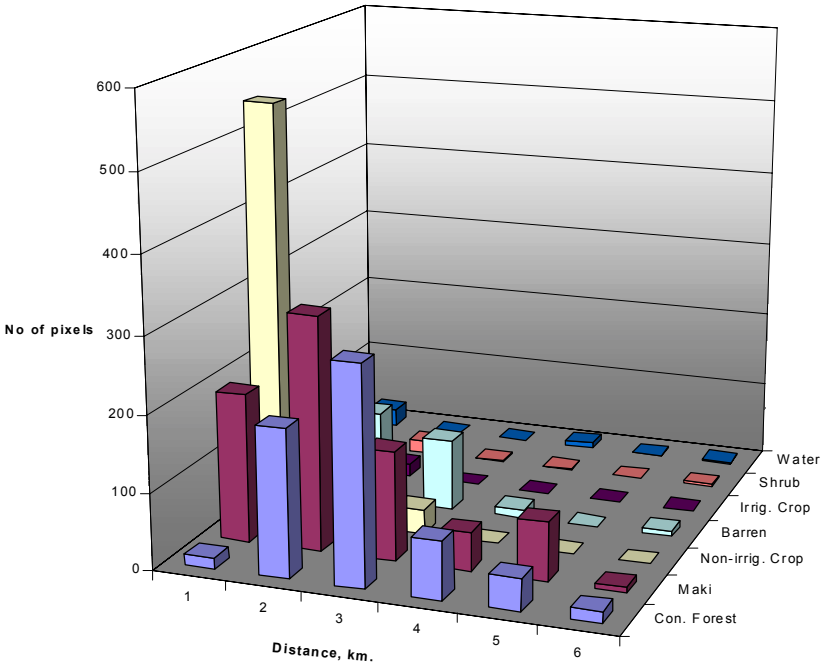

Figure 7: Distribution of the to-stream distances for each land cover for a typical sub-basin (ASA), Menderes Basin.

Table 4 summarizes the to-stream and down-stream data for selected land covers in Beydagi sub-basin, Küçük Menderes Basin.

Table 4: Physiographic data for selected land covers in Beydagi sub-basin, Küçük Menderes Basin.

Land cover	**Maki**	**Non-irrigated agriculture**	**Coniferous forest**
Average change in elevation, m, to nearest stream.	287.0	51.0	657.0
Mean. distance, km, to nearest stream	7.6	2.6	1.2
Standard deviation of distances to nearest stream.	3.3	1.8	3.3
Ave change in elevation, m, down stream	78.0	66.0	84.0
Mean. distance, km, down-stream	11.3	9.6	12.1
Standard deviation of distances down-stream	3.5	3.8	3.1

The total travel times are used in a lognormal smoothing filter to distribute the runoff from each land cover over time. The results are weighted by the percentages of the ASA covered by each land cover, converted to m^3/s, and added to the total flow of the ASA.

The distances and changes in elevation to-stream and down-stream are most easily computed using the TOPAZ (**TO**pographic **PA**rameteri**Z**ation) system described in more detail in Section 4.1. TOPAZ processes digital elevation data to define the stream courses and sub-basins and produce a series of raster images and output tables. The SLURPAZ program then processes the topographic outputs from TOPAZ together with land cover data to produce input files for the SLURP model.

Alternatively, the user could use GIS directly to compute the distances and changes in elevation and the land cover percentages for each ASA.

2.3 Routing between Sub-basins (ASAs)

Any imported streamflow (.FLI files from, for example, inter-basin transfers, groundwater originating from another basin or outflows from an upper part of the basin either observed or computed with some other model) are accumulated with the runoffs from all the land covers within the ASA and with any return flows from upstream irrigation projects (see section 2.4). The resulting flow must be routed from the outlet of this ASA to the outlet of the next ASA down the stream system, and so on until all the flows arrive at the outlet of the basin. The user

may choose to simply accumulate the flows from each ASA down the basin with no delay or attenuation (select N for no routing on the input screen for sub-basin routing, diversions and interventions) or may choose between Muskingum routing (select M) or Muskingum-Cunge routing (C). The linkages between ASAs are also specified on the input screen.

2.3.1 Muskingum Channel Routing

The Muskingum method developed by McCarthy in 1938 (quoted in Linsley, *et al.*, 1949) is a simple method of hydrological storage routing which makes use of two constants; the relative weight of inflow and outflow in computing channel storage, x, and the time of travel along the channel reach, K, to solve the storage equation. The outflow at time 2 (O_2) is computed from:

$$O_2 C_1 I_1 + C_2 I_2 + C_3 O_1 + C_4 \tag{27}$$

where I_1 , I_2 and O_1 are inflows at times 1 and 2 and outflow at time 1 respectively and C_1, C_2, C_3 and C_4 are constants defined by:

$$\begin{aligned} C_o &= KX + \nabla t / 2 \\ C_1 &= -(KX - \Delta t / 2) / C_o) \\ C_2 &= (KX + \Delta t 2) / C_o \\ C_3 &= (K - KX + \Delta t / 2) C_o \\ C_4 &= 0.5(q_1 + q_w)\Delta x \Delta t / C_o \end{aligned} \tag{28}$$

The values of x and K are specified for an ASA and will then be used to route flows from other ASAs through that ASA. The parameters are input on a screen in the SLURP sub-basin routing input window. K is measured in days and has an upper limit set to 9999 and x may vary from 0 to 0.5.

In this implementation of the Muskingum method, C_4 (local inflow) is not used. The effects of some typical values of x and K are as follows:

x = 0.0, K = 0; outflow hydrograph is the same as the inflow hydrograph
x = 0.0, K = 1; outflow hydrograph is lagged by 1 day but flows are the same
x = 0.25, K = 1; outflow is lagged by 1 day and the peak is reduced by about 10%.

If the TOPAZ/SLURPAZ programs are used to derive SLURP inputs, then K will default to 0.25 and K will be computed from the change in elevation down the channel, D, as (Institute of Hydrology, 1995):

$$K = 1.5e^{-D/250} \tag{29}$$

2.3.2 Muskingum-Cunge Channel Routing

The more exact Muskingum-Cunge channel routing method may be used if channel characteristics data such as length, change in elevation, average width, depth and roughness are available. This method assumes a single-valued depth-discharge relationship and uses the classical kinematic wave equation (Fead, 1986).

In this implementation, the storage constant, K, is computed as

$$K = \Delta x / c \tag{30}$$

where c is the kinematic wave speed and Δx is the channel length.

The kinematic wave speed, c, is computed from

$$c = 1.27\beta \frac{S_0^{0.3}}{q_0^{0.4}} n^{0.6} \tag{31}$$

where β depends on the cross-section shape and is assumed to be 5/3 for a rectangular channel, q_0 is a unit-width reference discharge and n is the Manning roughness factor.

The weighting constant, X, $0 \leq X \leq 1$, is calculated as

$$X = 0.5 \times \left(1 - \frac{q_0}{cS_0 \Delta x}\right) \tag{32}$$

where S_0 is the channel bottom slope. The data needed to rout flows using the Muskingum-Cunge method are input manually on screens such as Channel Routing Data and Flowpaths, Diversions & Interventions input screens.

2.3.3 Lake/Reservoir Routing/Regulation

Many river basins contain large lakes which modify the hydrograph of the river. If the stage-storage and stage-discharge relationships are known, then these may be used as an additional routing at the end of a sub-basin.

Similarly, if a sub-basin contains a dam and reservoir from which the outflows are controlled by a regulation plan, then this effect may also be simulated in SLURP.

Dam locations may be stored in file STRCTURS.INP and then converted to an IDRISI Vector Export Format using option:

\Tools\Convert .INP file to .VXP file.

The Vector Export file may then be imported to IDRISI and used as a vector overlay on a basin image (Figure 8).

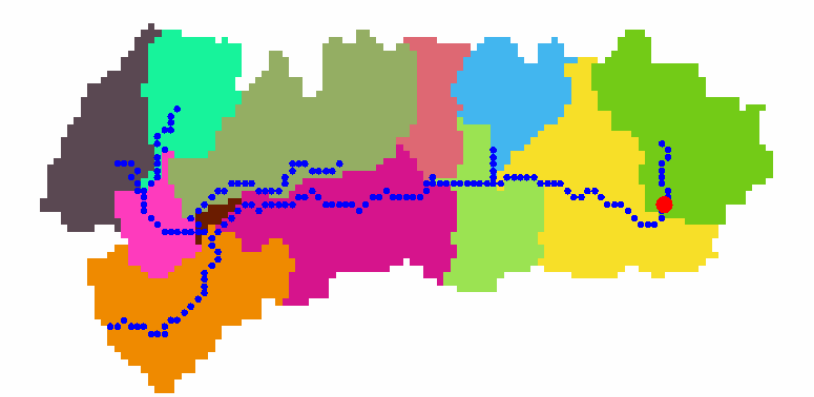

Figure 8: STRCTURS overlay showing proposed Beydagi reservoir site, Küçük Menderes Basin, Turkey.

Routing may be carried out either internally within the SLURP program or externally in a user-written program.

To specify that an ASA should use internal lake or reservoir routing, set the appropriate variable in the SLURP sub-basin routing, diversions and interventions input window to "I" and prepare a <Command_name>.RUT file with the routing specifications. In this file the user specifies the name of the ASA at which the reservoir routing takes place (there may be an unlimited number of ASAs with reservoir routing), the type of routing (specified outflows or natural), the parameters of the stage-area relationship, the stage-volume relationship (and the stage-discharge relationship, if appropriate) for the lake or reservoir, the maximum and minimum allowable reservoir levels and the starting and ending dates of each diversion period. Table 5 shows an example for Beydagi Reservoir in the Küçük Menderes Basin, Turkey.

Table 5: Example of part of a .RUT reservoir routing file for the Beydagi Reservoir in the Küçük Menderes Basin:

```
beydagi R 60
beydagi .036165 173. 1.52763
beydagi .019644 173. 2.44276
beydagi 240. 173.
beydagi 1994 1 1 1994 1 31 0.
beydagi 1994 2 1 1994 2 28 0.
beydagi 1994 3 1 1994 3 31 0.
beydagi 1994 4 1 1994 4 30 0.156
beydagi 1994 5 1 1994 5 31 2.658
beydagi 1994 6 1 1994 6 30 7.434
beydagi 1994 7 1 1994 7 31 9.828
beydagi 1994 8 1 1994 8 31 9.780
beydagi 1994 9 1 1994 9 30 9.60
beydagi 1994 10 1 1994 10 31 0.978
```

In this example, the Beyagi sub-basin contains a reservoir with outflows specified for the years 1985-198. The routing equations for the reservoir are:

$$\text{Area} = .036165 * (\text{level} - 173.)^{1.52763} \quad (33)$$

$$\text{Volume} = .019644 * (\text{level} - 173.)^{2.44276} \quad (34)$$

In these equations, the area is in $m^2 \times 10^6$, the volume is in $m^3 \times 10^6$ and the level is in meters. Figure 9 shows the SLURP-simulated regulated outflow from the proposed Beydagi Reservoir.

Such equations may be fitted to level, area and volume data by using program STADIS provided in directory \PROGRAMS\SLURP12\UTILITY on the SLURP CD-ROM.

If a sub-basin contains a water "land cover" and lake or reservoir routing/regulation is specified then the model compares the area of water in km^2 within the basin from the command file with the maximum surface area of the lake or reservoir. If the water area is greater than the lake area then this means that not all the water in the sub-basin is subject to routing. The water balance from the excess area is computed in the normal way and then the water within the lake or reservoir is routed or regulated. If the water area is less than the lake area then no vertical water balance is needed, only routing or regulation.

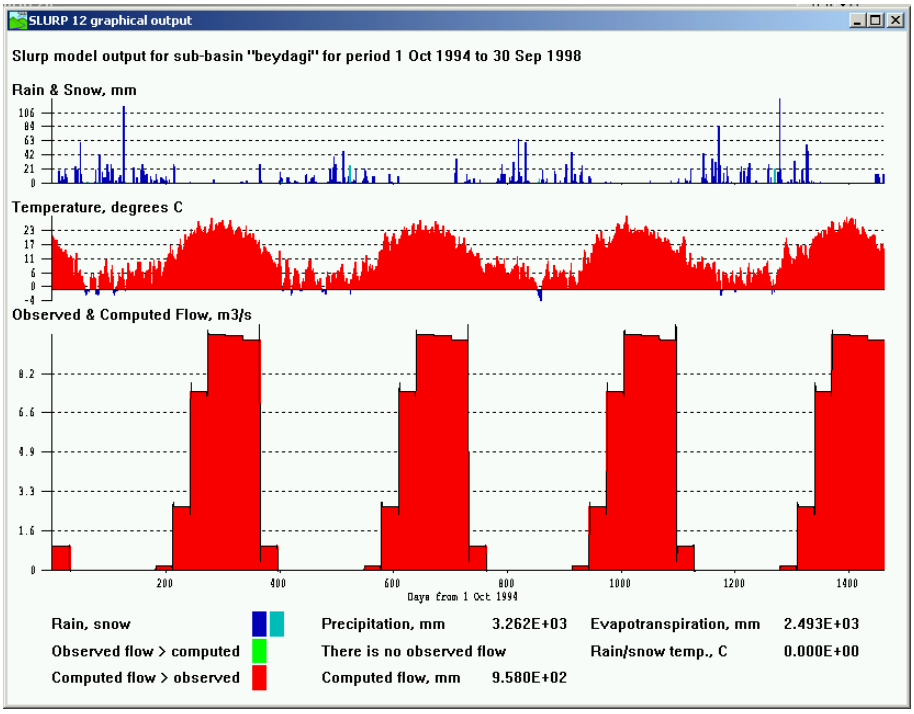

Figure 9: Hydrograph after passing through the reservoir routing procedure.

The SLURP basin model simulates the effect of routing and regulation for a lake or reservoir using the following steps for each day:

1. Compute the initial lake surface area and volume from an <ASA_name>.LVL file containing recorded daily levels.
2. Add the reservoir inflow and over-lake precipitation to the existing volume.
3. Subtract the over-lake evaporation from the volume.
4. Compute the new reservoir level and check for spill if the level exceeds the allowable maximum.
5. Check the regulation rules in file <command_name>.RUT to see if a release should be made today.
6. Make the release if appropriate and if the reservoir level is above the minimum allowed.
7. Recompute the volume and new level.

The example above is for a reservoir in which the outflow follows a series of specified releases. If the water body is a naturally regulated lake, then the outflow will not be specified but will depend on the lake level. In this case the first record of the .RUT file would appear as, for example,

beydagi N 0

indicating that Beydagi is a lake with natural routing. Following the stage-area and stage-volume parameters the user would include, in the same way, the parameters of the applicable stage-discharge curve:

$$\text{Discharge} = a * (\text{level} - b)^{c} \tag{35}$$

in which discharge is in m^3/s, the volume is in $m^3 \times 10^6$ and a, b and c are specified constants.

The SLURP model uses a modified Goodrich procedure (Goodrich, 1931) to solve the storage equation:

$$I_1 + I_2 \frac{2S_1}{t} - 0_1 = \frac{2S_2}{t} - 0_2 \tag{36}$$

in which I and 0 are inflows and outflows in m^3/s respectively, S is the reservoir volume in $m^3 \times 10^6$, t is the time interval in seconds and 1 and 2 indicate successive time steps. Equation 36 is solved by developing an equation relating $2S/t + 0$ to 0 from the specified stage-discharge and stage-volume equations.

Flows are then routed at successive time steps by computing the outflow from the initial reservoir level, finding $2S/t + 0$ from 0, converting to $2S/t$ and deriving the left hand side of Equation 36. The new outflow is then found from the right hand side of Equation 36.

If output for the ASA being routed is specified (in the Output Options window), and if the output is daily, then the lake/reservoir level, area, volume and output will be printed or saved to file <command_name>.PRN (Table 6).

Table 6: Example of routing output.

Date dd/mm/yyyy	Level m.	Area m2 * 10**6	Volume m3 * 10**6	Outflow m3/s
1 9 1988	2.20065E+02	1.97054E+01	2.21355E+02	1.04000E+01
2 9 1988	2.20037E+02	1.96735E+01	2.20793E+02	1.04000E+01
3 9 1988	2.20018E+02	1.96529E+01	2.20431E+02	1.04000E+01
4 9 1988	2.20005E+02	1.96378E+01	2.20166E+02	1.04000E+01
5 9 1988	2.19993E+02	1.96247E+01	2.19935E+02	1.04000E+01

The evaporation from a lake or reservoir may be computed in two ways. If the area of the lake or reservoir is relatively small (i.e. is only a fraction of the ASA area) then the method used will be one of the Morton CRAE, Granger, Spittlehouse/Black, Penman-Monteith or Linacre methods, just as is used for other land covers in the ASA.

However, for very large lakes the heat storage in the lake causes a lag in the annual evaporation cycle. To account for this the user can specify the use of the Morton lake model (Morton *et al.*, 1985). This evaporation model first computes monthly evaporations, then daily, and should be used for at least a complete year to allow for simulation of the seasonal changes in heat storage of the lake. It is this heat storage which results, for example, in Great Slave Lake having its maximum evaporation in September and October, long after the July/August peak air temperatures. At present, this option operates for complete calendar years of data only, i.e. January to December.

2.3.4 External Routing/Regulation

In some cases the simple lake or reservoir routing and regulation built in to the SLURP model and described above may not be adequate. For such cases, the user can prepare a computer program (in any language) to describe the transformation of inflow to outflow (which may also involve other data files), compile the program, link in any other routines needed, and name the resulting executable program SLURP12_RUT.EXE. The SLURP model will provide SLURP12_RUT.EXE with the data needed for routing/regulation. SLURP12_RUT should carry out the reservoir routing or regulation and write the results to data files. SLURP will then read the results of the routing/regulation and continue with the rest of the simulation.

External lake or reservoir routing/regulation for an ASA is specified in the option

\Edit\Flow paths, diversions, interventions

on the main SLURP menu.

2.4 Diversions and Interventions

2.4.1 Diversions

In many basins regulatory structures exist to divert water from the river for hydropower, water supply or irrigation (see Figure 10). To specify in SLURP that an ASA has diversions, use the input screen in the Flowpaths, Diversions & Interventions input window and prepare a <Command_name>.DIV file with the diversion specifications. In this file, specify the name of the ASA at which the diversion takes place (there may be an unlimited number of diversions at any ASA), the names of the file(s) to contain the diverted water(s) and the details of each diversion. Table 7 below gives a simple example.

Table 7: Example of a .DIV diversion file for the Selçuk sub-basin, Küçük Menderes Basin

```
selcuk  1 35
selcuk selcuk.exr
selcuk 1994 4 1 1994 4 30 0.104  0.0
selcuk 1994 5 1 1994 5 31 1.772  0.0
selcuk 1994 6 1 1994 6 30 4.956  0.0
selcuk 1994 7 1 1994 7 31 6.552   0.0
selcuk 1994 8 1 1994 8 31 6.520  0.0
selcuk 1994 9 1 1994 9 30 9.60   0.0
selcuk 1994 10 1 1994 10 31 0.652  0.0
```

Diversions from the river may be made to two types of file, .SIR and .EXR.

In SLURP, water diverted may be used as irrigation supply for any land cover in any downstream sub-basin (ASA). Diversions for irrigation water must be written to files labelled <ASAname>.SIR where <ASAname> refers to the ASA containing the irrigated area and SIR stands for **S**urface **IR**rigation. Any water remaining in an SIR file after use for irrigation will be added to the outflow from the irrigated ASA.

Water being consumed in the basin or exported from the basin must be written to files with the name <ASAname> .EXR where <ASAname> is the name of the ASA at which the EXtraction from the basin takes place. In this way they will be recognized by SLURP to get the basin water balance correct. There is no provision for return flows from an .EXR file and so water withdrawals for urban and industrial use within the basin should be specified as only that portion of the total water use which is consumed. For water exported from the basin, the full withdrawal should be specified.

If the river does not contain sufficient flow to meet the total diversion demand, the diversions will be reduced proportionately to equal the river flow. In the .DIV file, the user may also specify a minimum allowable flow in the river for environmental or dilution purposes, for example. In

this case, the requested diversions will be reduced as necessary to maintain this minimum flow in the main river.

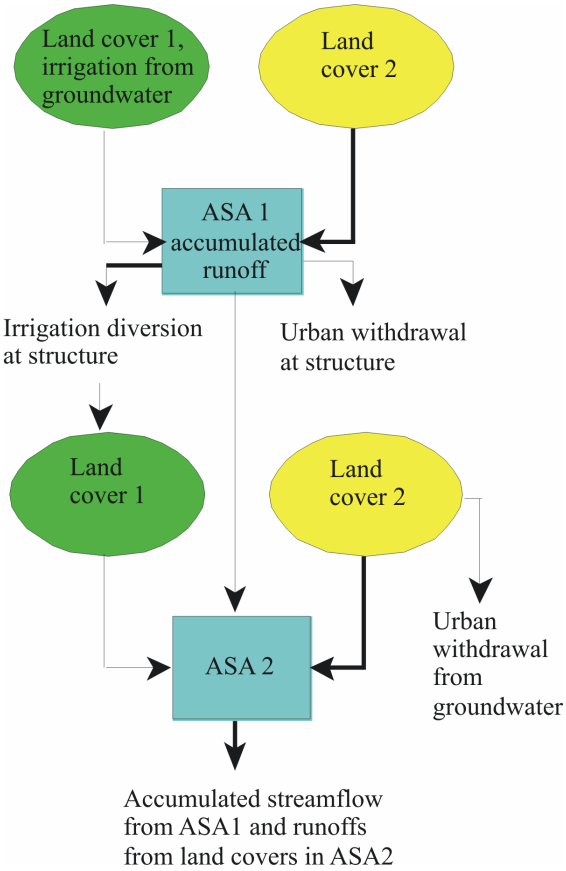
Land cover 1, irrigation from groundwater
Land cover 2
ASA 1 accumulated runoff
Irrigation diversion at structure
Urban withdrawal at structure
Land cover 1
Land cover 2
ASA 2
Urban withdrawal from groundwater
Accumulated streamflow from ASA1 and runoffs from land covers in ASA2

Figure 10: Diversions and interventions in the vertical water balance of the SLURP basin model.

2.4.2 Interventions in the Vertical Water Balance

Section 2.4.1 has discussed how water may be diverted from the river for irrigation or consumption using a regulatory structure at an ASA outlet. The use of this water for irrigating a particular land cover (crop) in a particular ASA is treated as an intervention in the vertical water balance of that land cover. Extraction of groundwater for consumption by urban or industrial users or for export from the basin is also treated as an intervention in the vertical water balance.

An intervention is specified by putting 'Y' for each affected ASA on the Flowpaths, Diversion & Interventions data input screen. As the model simulates the vertical water balance, it checks this parameter and, if applicable, the model will read an intervention file <Command_name>.INT and follow the rules for each land cover.

File <Command_name>.INT should be prepared as shown in Table 8 below. The program MAKE_INT.F is provided in directory \PROGRAMS\SLURP\UTILITY on the CD-ROM as an example of an automated procedure to prepare a .INT file. Each record of the file contains information on the ASA, land cover, type of intervention, start and end dates of the intervention and the rate of intervention. The file may contain any number of records but a particular date for a particular land cover within a particular ASA may occur in only one record.

Table 8: Example of part of a .INT intervention file for the Gediz Basin.

```
medar    non-irrig. X  1986 1   1 1998 12 31 0.0060 N N medar.exg
gordes   non-irrig. X  1986 1   1 1998 12 31 0.0015 N N gol.exg
gordes   coniferous X  1986 1   1 1998 12 31 0.0013 N N gordes.exg
gordes   maki       X  1986 1   1 1998 12 31 0.0839 N N izmir-1.exg
kum      maki       X  1986 1   1 1998 12 31 0.0026 N N surahan.exg
kum      non-irrig. X  1986 1   1 1998 12 31 0.1305 N N izmir-2.exg
selendi  coniferous X  1986 1   1 1998 12 31 0.0003 N N selendi.exg
```

If the intervention is for irrigation then the .INT record will specify the source of the water (surface or groundwater) and the type of irrigation (sprinkler or furrow). If the irrigation source is specified as surface water, then SLURP will read the appropriate .SIR file generated by diversion from the river (see previous section) and check that enough water is available for the requested irrigation rate. The actual rate used will be the smaller of that requested and that available. Excess water will be returned to the ASA outlet. Groundwater for irrigation is taken from the slow store

Interventions may also be used to withdraw groundwater for urban or industrial water consumption or for export from the basin. This will be taken from the slow store of the appropriate ASA and land cover. For water use within the basin, only the actual consumptive use should be withdrawn. For water exports from the basin, the full water demand should be used. The intervention file must specify the file to which water withdrawals will be written as <anyname.EXG>.

2.5 Calibrating the Parameters

In an ideal model, all parameters would be physically based and easily measured and calibration would be unnecessary. However, given the extreme variability in hydrological conditions across a basin, this ideal state is unlikely ever to be reached. The SHE model is probably one of the most physically realistic of current models, requiring vast numbers of distributed data; yet even SHE needs to be calibrated for practical applications (Refsgaard *et al.*, 1992). SLURP uses parameters which may be estimated directly for different land classes (e.g. Manning's n, infiltration rate, hydraulic conductivity, soil depths, etc.) but, because the model is distributed and the land class parameters are applied over large areas, some form of calibration is often necessary. Once parameters have been derived for a particular set of land classes the model may be applied to other basins which contain the same land classes without any further calibration.

Table 9 lists the parameters of the model and shows which are measured, estimated, or calibrated. The sensitivities of the various parameters are classed as **L**ow, **M**edium or **H**igh.

Table 9: Typical parameters for the SLURP model.

Parameter name	**How derived**	**Sensitivity**
Initial contents of snow store*[1]	Measured/ Estimated	Medium
Initial contents of slow store*[1]	Estimated	Low
Maximum infiltration rate*[1]	Estimated	Low
Manning roughness surface*[1]	Estimated	Low
Retention constant fast store*[1]	Estimated	High
Max. capacity fast store*[1]	Measured/ Estimated	High
Retention constant slow store*[1]	Estimated	High
Max. capacity slow store*[1]	Measured/ Estimated	Medium
Precipitation factor*[1]	Estimated	High
Snow melt temperature*[1]	Estimated	Medium
Temperature lapse rate	Measured/ Estimated	Medium
Precipitation lapse rate	Measured/ Estimated	Low
Initial contents of canopy store	Null	Low
Initial contents of fast store	Null	Low
Max. capacity of canopy store	Estimated	Medium
Albedos (surface, snow)	Measured/ Estimated	Medium
Leaf area index	Measured/ Estimated	Medium
Interception coefficients a, b	Estimated	Medium
Soil heat flux	Estimated	Low
Areas of the land covers	Measured (GIS)	Medium
Elevations of the land covers	Measured (GIS)	Medium
Distances to stream	Measured (GIS)	Medium
Distances downstream	Measured (GIS)	Medium
Changes in elevation to stream	Measured (GIS)	Medium
Changes in elevation downstream	Measured (GIS)	Medium
Snow melt rates and radiation coeff.	Estimated	High
Muskingum routing coeff. x, K*[1]	Estimated	Low
River geometry	Measured/ Estimated	Low
Priestley-Taylor coefficients*[2]	Estimated	Medium
Aerodynamic roughness or wind func*[2]	Estimated	Low
Field capacity, wilting point, porosity*[2]	Measured/ Estimated	Medium

** [1] Parameter can be included in the calibration procedure, * [2] Parameter is optional.*

Many of the parameters in Table 9 together with the between-ASA routing coefficients may be calibrated. Other parameters are more easily measured or estimated and need not be included in any automated optimization. The precipitation factor, P(9), and the snowmelt temperature, P(10), are redundant in most cases and should be set to 1.0 and 0.0 respectively although, as noted earlier, P(9) may be used to compensate for gauge undercatch and P(10) may be used to bias the precipitation distribution to snow or rain. The effect of elevation on precipitation and temperature are accounted for by non-calibrated rates of change per 100 meters elevation. If the model run is started during the fall season when there is no snowpack and soil moistures are low, then the initial contents, P(1) and P(2) may be set to zero or low values and do not need to be optimized.

For the "water" land cover, the only parameters needed are an initial snow water equivalent (if there is a snowpack), an optional precipitation factor and an optional snowmelt temperature. If a snowpack is a possibility then snowmelt rates and snow albedos will also be needed.

The goodness of fit of the SLURP model may be judged both graphically and from statistical criteria. After each year of model simulation the observed and computed ASA hydrographs may be displayed on screen. The model generates statistics for the recorded and simulated streamflows for each ASA.

The statistics include four measures of efficiency which may be used to measure the effectiveness of the calibration or simulation:

a) The Nash/Sutcliffe efficiency (Nash & Sutcliffe, 1970):

$$F^2 = \frac{F_m^2 - F_d^2}{F_m^2} \tag{37}$$

where

$$F_m^2 = \frac{1}{n}\sum_{i=1}^{n}(q_i - \bar{q})^2 \tag{38}$$

and

$$F_d^2 = \frac{1}{n}\sum_{i=1}^{n}(q_i - c_i)^2 \tag{39}$$

n is the number of days, q_i is the observed flow on day i, c_i is the simulated flow on day i and $\bar{q}$ is the average measured flow. Martinec & Rango (1989) have discussed the implications of defining q as either the average flow over the period in question or as the long-term mean flow.

b) The Garrick efficiency measure (Garrick *et al.*, 1978) in which F_m^2 in (37) above is replace by:

$$F_m^2 = \frac{1}{n}\sum_{i=1}^{n}(q_i - \bar{q}_i)^2 \tag{40}$$

where $\bar{q}_i$ is the long-term mean flow on day *i*. This is a more stringent criterion as it compares the model simulation on a particular day to the long-term mean for that day. This criterion is also known as the Coefficient of Gain from Daily Means (WMO, 1986).

c) The Previous-Day criterion (Kite, 1991). Given no other information, one possible estimate of flow on day i might be the flow on the previous day, *i*-1, taking advantage of the persistence component of river and lake time series. A suitable measure of efficiency replaces F_m^2 in (37) above with:

$$F_m^2 = \frac{1}{n}\sum_{i=1}^{n}(q_i - q_{i-1})^2 \qquad (41)$$

The sensitivity of the first three criteria to changes in the parameter values is very different. It is easy to calibrate the model to give a high value of the Nash/Sutcliffe statistic, less easy to improve the Garrick statistic, and very difficult to obtain a calibration with a high value of the Previous-Day criterion. Figure 11 shows an example of the variation in (from the top) Nash/Sutcliffe, Garrick and Previous-Day as the values of two parameters are stepped across a grid. The three criteria are all displayed to the same scale and clearly show the relative sensitivity.

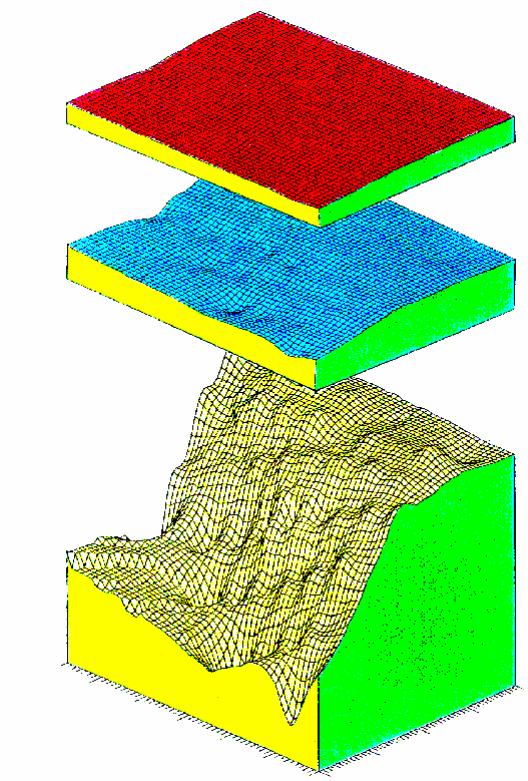

Figure 11: Relative sensitivities of three performance criteria used in the SLURP basin model as two parameters are changed in a regular grid pattern.

d) The fourth criterion computed in the model is the deviation of runoff volumes, D_v, (WMO, 1986):

$$D_v(\%) = 100\frac{V_m - V_c}{V_m} \tag{42}$$

where V_m is the measured volume of runoff and V_c is the computed volume of runoff over the period of interest. This criterion is simply a transformation of the mean computed and observed flows for the simulation period. A negative value of D_v means that the mean computed flow is too high. This is somewhat counterintuitive and it might have made more sense for WMO to reverse D_v so that a positive criterion would indicate an excess of simulated water.

The Student's 't' test is often used to test the hypothesis that observed and computed values are not significantly different from each other and to determine at what level of significance this hypothesis may be true:

$$t = \frac{r\sqrt{(n-2)}}{\sqrt{(1.0-r^2)}} \tag{43}$$

where r is the simple correlation coefficient between q and c.

It is common to compare observed and computed streamflows in graphical form and to fit a simple linear regression such as

$$q = a + b.c \tag{44}$$

to the two sets of data. In a good simulation, the intercept of such a regression, a, would be zero and the slope, b, would be 1.0. The actual values may be computed as:

$$b = \frac{\sum_{i=1}^{n}(q_i c_i) - \left(\sum_{i=1}^{n} q_i\right)\left(\sum c_i\right)/n}{\sum_{i=1}^{n} q_i^2 - \left(\sum_{i=1}^{n} q_i\right)^2/n}$$

$$a = \frac{\sum_{i=1}^{n} c_i - b.\sum_{i=1}^{n} q_i}{n} \tag{45}$$

While the four criteria may be output to screen, printer or data file, Student's 't' statistic and the regression coefficients may only be output to the printer or a data file.

Changes to the model parameters may be made to improve model results (if necessary) in three ways:

i) By changing individual parameter values, making a series of simulations and comparing the criteria values and generated hydrographs.
ii) By using the built-in Shuffled Complex Evolution (SCE-UA) optimization method (Duan *et al.*, 1994). The SCE-UA method is very suited to hydrological models as it avoids the many local minima that may exist (see, for example, the peaks and valleys in Figure 11).
iii) By preparing files for the PEST (Watermark Numerical Computing, 2000). This method is model-independent.

3. DATA REQUIREMENTS FOR THE SLURP HYDROLOGICAL MODEL (12.2)

The SLURP model requires three types of data to model a natural system; point (station) data such as time series of precipitation and air temperature, areally-distributed data such as topography and land cover and, finally, model parameters and coefficients such as albedos and infiltration rates. To include modifications to the natural regime, additional data will be needed.

Of course the model uses digital data, but the first step in any basin study is to collect paper. Maps at an appropriate scale (usually 1:100,000 or better) are needed showing the topography, the river distribution, the locations of important cities, river diversions and water input/extraction points and the locations and sizes of irrigation schemes, lakes, reservoirs and any other features to be modelled. The topography and river network will be used as checks on the automatic river network derived in the model (all digital elevation data contain errors) and the locations of cities, irrigation schemes, lakes, dams, diversions and water input/extraction points will be used to site these features in the hydrological model. Maps showing the locations of climate stations, meteorological and hydrometric stations may be needed to check the positions and elevations of these stations contained in the corresponding digital data (not all information in data files is correct). Finally, information on the operating rules of dams and reservoirs, the crop pattern and watering rules of irrigation schemes and any diversions or consumptive uses will be needed.

The next step is to collect climate data for as many stations as possible within and close to the study basin and flow data for as many stations as possible on the main river, tributaries and distributaries. The third step is to obtain a digital elevation model and a land cover dataset. Finally data for the model parameters should be obtained. The next sections of this report give further information on each of these steps.

3.1 Point (Station) Data

The vertical water balance within the SLURP model converts precipitation data into evapotranspiration, runoff and changes in soil and groundwater storages. To do this the model needs climate data, either as recorded at climate stations or as output by an atmospheric model. The following time series of data are required:

- daily mean air temperature
- daily dewpoint temperature or relative humidity
- daily total precipitation
- daily global radiation or hours of bright sunshine or ratio of observed to maximum possible hours of bright sunshine.

Other optional time series that may be used include:

For calibration:
- observed daily discharge

For calculation of the Garrick performance criterion:
- long-term mean daily discharges.

Any of four methods of computing evapotranspiration may be used in the SLURP model. If the user selects the Morton method, then the following is needed:
- long-term mean annual precipitation

If the user selects either the Granger or the Penman-Monteith method of computing evapotranspiration, then the following is needed:
- daily wind speed

Optionally, the following data from satellite may be used:
- daily cloud cover
- daily snow cover
- snow water equivalent from satellite or from snowcourses

If the basin contains large lakes or reservoirs which must be simulated in the model, then the following will be needed:
- observed lake or reservoir levels

All of the point or station data are stored in separate files for each data type. Each file is given a name made up of the station name and a three-character extension as <Station Name.xxx> where the extensions xxx are listed in the following table for each type of data. The most important data types needed are the .PCP, .TAV, .TDP (or .RHU) and .GLO (or .SUN). All station data files are sequential and unformatted. Data files for different basin studies should be stored in separate directories.

Any data needed specifically to control the evapotranspiration computations are held in separate files for each evapotranspiration method. For Morton, the mean annual precipitation (and the mean lake depth when needed for computation of lake evaporation) are stored in file <Command_name.MOR>. For Spittlehouse/Black, the Priestley-Taylor coefficient, beta, and the field capacity and wilting point for each land cover type is held in the file <Command_name.SB>. Granger evapotranspiration uses a file <Command_name.GRA> that contains an aerodynamic resistance or a windspeed function for each land cover depending on whether wind speed data are available or not. The Penman-Monteith method uses file <Command_name.PM> while the Linacre method uses <Command_name.LIN>. These files will all be created automatically as the user fills in the on-screen forms in SLURP and the user does not need to be concerned with formats. The expression <Command_name> is usually the name of the basin being modelled.

Table 10: Data types used in the SLURP basin model.

Data Type	File Extension	Input or Output	Units
command file	CMD	I	various
precipitation	PCP	I	Mm
air temperature	TAV	I	Cº
dewpoint temperature	TDP	I	Cº
relative humidity	RHU	I*	decimal
average wind speed	WND	I*	m/s
incident global radiation	GLO	I	$w/m^2/day$
hours of bright sunshine	SUN	I*	hours or % .
cloud cover	CLD	I*	percentage
snow covered area	SNO	I*	percentage
snow water equivalent	SWE	I*	mm
recorded streamflow	FLO	I*	m^3/s
streamflow imported to an ASA	FLI	I*	m^3/s
long-term mean streamflow	LTM	I*	m^3/s
inputs for Morton CRAE evapotranspiration option	MOR	I*	various
inputs for Granger evapotranspiration option	GRA	I*	various
inputs for Spittlehouse/Black evapotranspiration option	SB	I*	various
inputs for Penman-Monteith evapotranspiration option	PM	I*	various
inputs for Linacre evapotranspiration option	LIN	I*	various
specifications for reservoir operation	RUT	I*	various
specifications for diversions operation	DIV	I*	various
daily lake or reservoir levels used for routing	LVL	I*	m
specifications for interventions in vertical water balance of a land cover	INT	I*	various
specifications for changes to land cover	LCC	I*	various
specifications for PET outputs	MAP	I*	mm
calculated streamflow	FLC	O	m^3/s
log of optimization activity	OPT	O	text
complete daily water balance	PRN	O	various
ASA hydrographs, precip., temperature	PLT	O	mm & m^3/s
store contents	STO	O	mm
surface water diversions from an ASA for irrigation	SIR	O	m^3/s
water diverted from a river for consumption or export	EXR	O	m^3/s
water extracted from groundwater for consumption or export	EXG	O	m^3/s
input file for lake evaporation	WRI	O	various
output file for lake evaporation	WRO	O	various
output file with annual PET data	PET	O	mm
output file with PET data for specific dates	DAY	O	mm
output file with daily PET data at specific ASA/land cover combinations	TIM	O	mm

** signifies data which are optional depending on choice of analysis and model output requirements.*

All the climate station and streamflow data used in SLURP are contained in unformatted space-delimited ASCII data files. Each record of these files contains the data for one day arranged in the order: year (4-digit integer), month (2-digit integer), day (2-digit integer) and data (real, including decimal point). The following shows a part of such an unformatted space-delimited ASCII data file listing daily precipitation in mm at a particular climate station for the period 8-14 October 1994.

```
1994  10   8    0.00
1994  10   9    0.00
1994  10  10    0.11
1994  10  11    2.62
1994  10  12   12.81
1994  10  13    0.00
1994  10  14    0.96
```

All data files must be for the complete period of the intended model run including days with missing data (specified as -99999.99). For each climate station, obtain and retain the station location either as latitude and longitude or as UTM coordinates and obtain the station elevation.

The sets of data observed at climate stations or simulated by atmospheric models will be converted by SLURP to climate data sets for each sub-basin or ASA. The model uses the Thiessen polygon method with weights computed from the DEM in the topographic analysis routines. The differences in elevation between the climate stations and the sub-basins are also used to correct the climate station data.

Traditionally, hydrological models have depended on locally collected climate data. However, in many countries, such data are becoming difficult to obtain either because of lengthy processing times or high data costs. Instead, we can obtain many data from databases held on the Internet. Currently, there are two main global datasets of daily climate data; GDS (Global Daily Summary) and GSOD (Global Surface Summary of the Day), both provided by NOAA from NCDC data collections at website http://www.ncdc.noaa.gov/cgi-bin/res40.pl. GDS is also available from the IWMI Climate Atlas and from the USGS Hydrolab website (although the format of the latter is uncertain) and GSOD is also available from the University of Miami website. GDS contains daily maximum and minimum temperatures and daily precipitation from over 10,000 stations for the period 1977-1991 in metric units. GSOD contains 13 parameters for over 8000 stations for the period 1994 to date, is updated on the web every month and is in imperial units.

The SLURP CD-ROM contains programs to extract and process GDS and GSOD data sets. GDS has neither radiation nor humidity data and GSOD does not have radiation data. Approximations for humidity and radiation described in the manual and included in programs included on the CD-ROM may be used to complete missing data sets.

Observed daily streamflow data (.FLO files) are, optionally, used in the SLURP model for calibration. These may be obtained from hydrometric station records in the country concerned or (sometimes) from websites such as ORNL: http://www-eosdis.ornl.gov. Long-term mean daily

streamflow (.LTM files) are, optionally, used to compute the Garrick performance statistic. Additional streamflow data (.FLI files) may be used to include inflows from sources such as inter-basin transfers or groundwater originating from another basin. These inflows can also be used in cases where SLURP is used to model only part of a basin and the inflows are actually outflows from an upper part of the basin (either observed or computed with some other model).

3.2 Topographic Data and Land Cover Data

SLURP requires information on slopes and distances to move water from the top to the bottom of the basin. Raw elevation datasets (digital elevation models, DEMs) such as ETOPO5 which provides 5-minute resolution data and GTOPO30/HYDRO1K which provide 30-second gridded elevation data for the world are manipulated by SLURP's ancillary topographic analysis routines to yield the derived inputs required by the SLURP model.

The easiest way to obtain the DEM is to download the tile for the basin area from an Internet site (http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html) such as that for the USGS GTOPO30 DEM. After uncompressing, the file may be imported into IDRISI or a similar GIS. After extracting a window covering the basin, the DEM may be exported from IDRISI in the ASCII flat file format required by the SLURP topographic analysis routines. The full procedure is described in detail in the SLURP manual; all the user needs to know at this stage is how to download the raw data.

The following figure shows an example of a DEM for the Küçük Menderes Basin in western Turkey.

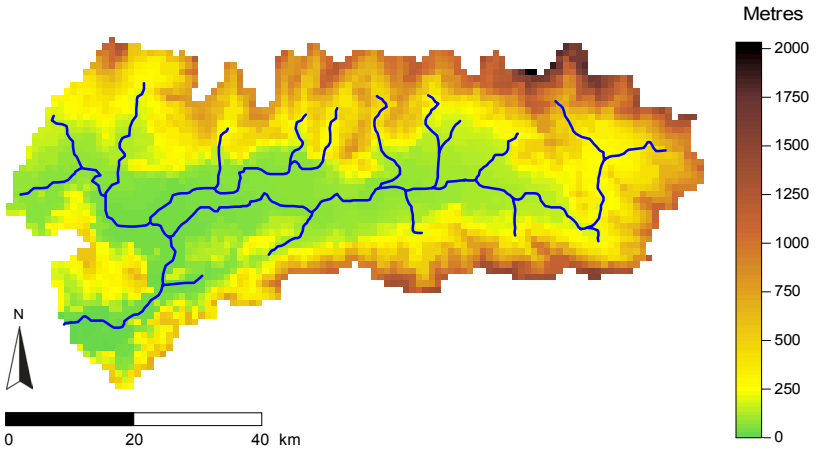

Figure 12: DEM for the Küçük Menderes Basin in western Turkey.

At the same time, the topographic analysis routines use land cover raster data such as the USGS global dataset derived from satellite sensors such as NOAA AVHRR or Landsat TM/MSS. There are many different global land cover classification schemes at many different scales. For many basins the U.S. Geological Survey's (USGS) Earth Resources Observation System (EROS) Data Center 1-km resolution global land cover characteristics data base available from the USGS website http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html will be suitable. Just as with the DEM, the land cover image may be imported into IDRISI after unpacking. The image must now

be made to correspond to the DEM image by converting from the Lambert Azimuthal Equal Area projection to the UTM projection and by forcing the image to the same number of rows and columns. Finally, the land cover image must be converted to an integer ASCII file named LCLASS.INP and exported for use by the SLURP ancillary topographic analysis routines. Again, the full procedure is described in detail in the SLURP manual.

The following figure shows an example of a land cover dataset for the Küçük Menderes Basin in western Turkey.

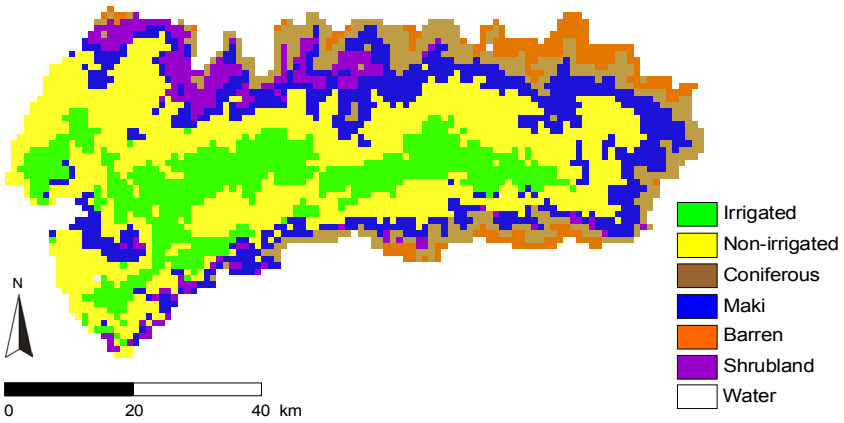

Figure 13: A land cover dataset for the Küçük Menderes Basin in western Turkey.

The topographic analysis routines derive the following information from the DEM and the land cover dataset:

- A division of the basin into sub-basins (known in the model as aggregated simulation areas or ASAs).
- Percentages of each sub-basin (ASA) area occupied by different land covers.
- Main channel length and change in elevation in the sub-basins (ASAs).
- Means and standard deviations, for each land cover, of differences in elevation to the nearest point on a stream for each sub-basin (ASA).
- Means and standard deviations for each land cover of differences in elevation along the stream to the outlet of each sub-basin (ASA).
- Means and standard deviations for each land cover of distances to the nearest point on a stream for each sub-basin (ASA).
- Means and standard deviations for each land cover of distances along the stream to the sub-basin (ASA) outlets.
- Mean latitude and altitude of each sub-basin (ASA).
- Areas of influence for climate stations.
- Mean annual precipitation for each sub-basin (ASA).
- Sequence of sub-basins (ASAs) within the basin.

The routines automatically convert the data into the format used by the model. The sequence of events is shown in Figure 14. Details are in the SLURP manual but, at the data collection stage, are not needed.

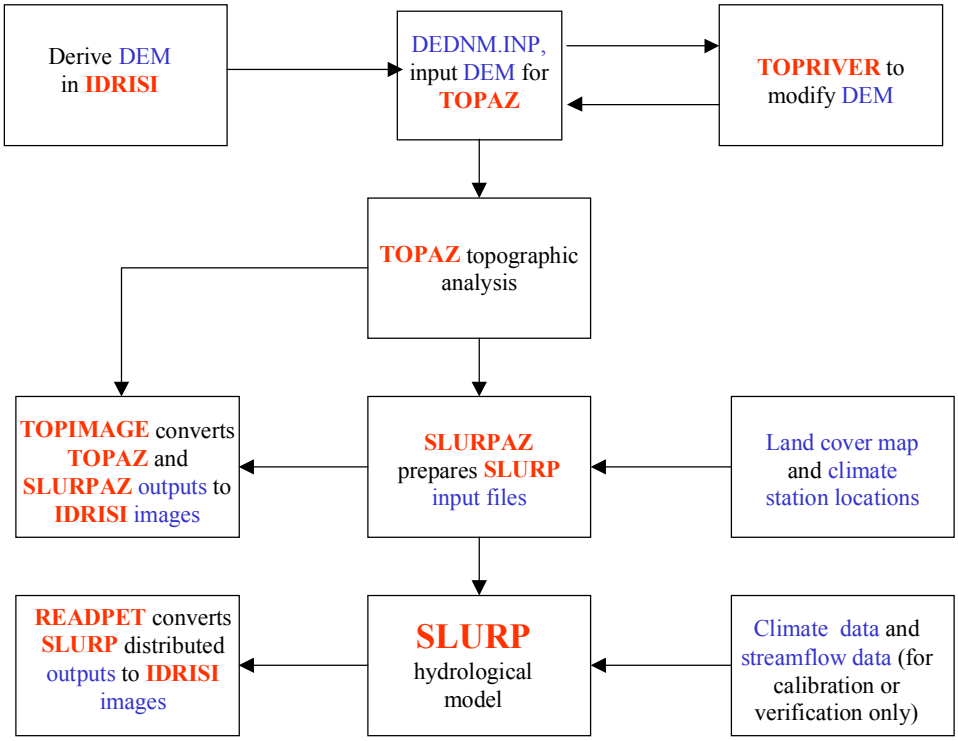
Derive DEM in IDRISI
DEDNM.INP, input DEM for TOPAZ
TOPRIVER to modify DEM
TOPAZ topographic analysis
TOPIMAGE converts TOPAZ and SLURPAZ outputs to IDRISI images
SLURPAZ prepares SLURP input files
Land cover map and climate station locations
READPET converts SLURP distributed outputs to IDRISI images
SLURP hydrological model
Climate data and streamflow data (for calibration or verification only)

Figure 14: Sequence of topographic analysis routines.

3.3 Model Parameters and Coefficients

A hydrological model attempts to simulate the physical processes involved in the transformation of precipitation into evapotranspiration and runoff. Model parameters control the way in which this transformation is carried out through such processes as interception, infiltration and snowmelt. Parameters include:

- maximum capacities for the canopy, detention store and slow store.
- initial contents of the snowpack and fast and slow stores.
- initial contents of the snowpack and fast and slow stores.
- interception coefficients, and maximum and minimum leaf area index (LAI).
- surface albedo and maximum soil heat flux.
- snowmelt rates and energy conversion factors.
- saturated infiltration rate.
- conductivity.
- roughness coefficient for each land cover and for the channel within the ASA.
- lapse rate for temperature and precipitation/elevation adjustment rate.
- parameters for specific evapotranspiration methods such as windspeed function, wilting point, field capacity and Priestley-Taylor coefficient.

Table 11 summarizes typical values of some of the parameters used in SLURP. Model parameters may be obtained from field measurements (although be aware that measurements in the field are usually point measurements while SLURP uses areal averages – the two may not be the same) or from previous experience in a similar basin (parameter sets for several basins are included on the SLURP CD-ROM). The model parameters are put into a data file known as <Command_name.CMD> where Command_name is usually the name of the basin being modelled by filling in fields on the SLURP screens using \EDIT.

Table 11: Some typical parameter values for different land cover types.

Land Cover	Wilting point as fraction of soil water	Field capacity as fraction of soil water	Albedo	Maximum infiltration mm/ day	Ave. Snowmelt rate mm/ day	Wind speed fctn	Priestley Taylor Alpha	Beta
Deciduous Forest	0.05	0.25	0.15	100	2	25	1.26	10
Coniferous Forest	0.05	0.25	0.12	100	2	25	1.26	10
Mixed Forest	0.05	0.25	0.14	100	2	25	1.26	10
Crop&grass	0.05	0.25	0.23	40	5	17	1.26	15
Bare Soil	0.05	0.25	0.25	20	5	12	1.26	15

4. TOPAZ (3.12) DIGITAL TERRAIN ANALYSIS MODEL

4.1 Background

Topography is important to the description, quantification and interpretation of many biosphere processes. Examples of such processes in the field of hydrology include: surface runoff and water storage, energy fluxes, evapotranspiration, soil erosion and snow metamorphosis. Extracting topographic information for a watershed by traditional, manual techniques can be a tedious, time consuming, subjective, and error-prone task, particularly for large watersheds. Research over the past decade has demonstrated the feasibility of extracting topographic information directly from raster Digital Elevation Models (DEM). In the field of water resources and hydrology, automated evaluation of DEMs has focused on watershed segmentation, definition of drainage divides and identification of the drainage networks. This automated extraction of network and sub-watershed properties from DEMs represents a convenient and rapid way to parameterize a watershed. The increasing commercial availability of DEM coverage for many areas of the United States and advances in DEM processing makes an automated approach to watershed parameterization a practical and useful alternative to manual techniques. Automated techniques also have the advantage of generating digital data that can be readily imported and analyzed by Geographic Information Systems (GIS).

The TOPAZ software (**TO**pographic **PA**rameteri**Z**ation) is a digital landscape analysis tool that provides comprehensive processing and evaluation of raster DEMs to identify topographic features; measure topographic parameters; define surface drainage; subdivide watersheds along drainage divides; quantify the drainage network; and, calculate representative subcatchment parameters. TOPAZ emphasizes consistency between all derived data, the initial input topography, and the physics underlying energy and water flux processes at the landscape topography. The primary objective of TOPAZ is to support hydrologic modelling and analysis, but it can also be used to address a variety of geomorphological, environmental and remote sensing applications. TOPAZ is not a GIS in the traditional sense, but is a system of software programs that performs numerical processing of raster DEMs and produces a number of data layers and attribute tables. Data layer algebra and monitor display capabilities are not included in TOPAZ. For such functions TOPAZ relies on a user-selected GIS. The interface to a GIS is provided through generated raster files.

The purpose of this section is to provide an overview of the fundamental concepts, capabilities and limitations of the software; underlying methods and models; organization and operation of the software; input requirements and output; and, available documentation.

4.2 Fundamentals and Program Capabilities

4.2.1. Fundamental Concepts

The DEM processing in TOPAZ is based on the D8 method, the downslope flow routing concept, and the critical source area (CSA) concept. The D8 method (Douglas, 1986; Fairfield and Leymarie, 1991) defines landscape properties for each individual raster cell by the evaluation of itself and its 8 immediately adjacent cells. The downslope flow routing concept defines the drainage and flow direction on the landscape surface as the steepest downslope path from the cell of interest to one of its 8 adjacent cells (Mark, 1984; O'Callaghan and Mark, 1984; Morris and Heerdeger, 1988). The CSA concept defines the channels draining the landscape as those raster cells that have an upstream drainage area greater than a threshold drainage area, called the critical source area (CSA). The CSA value defines a minimum drainage area below which a permanent channel is defined (Mark, 1984; Martz and Garbrecht, 1992). The CSA concept controls the watershed segmentation and all resulting spatial and topologic drainage network and subcatchment characteristics.

These methods and concepts have been applied previously in DEM processing algorithms (above references and: Jenson and Domingue, 1988; Martz and DeJong, 1988; and others). TOPAZ builds upon and extends that work. A number of the limitations of previous work with respect to drainage identification in depressions and over flat surfaces have been overcome in TOPAZ, and a number of new features have been added to address specific hydrologic and hydraulic needs (Garbrecht and Martz, 1996). TOPAZ is designed to provide interrelated landscape analysis functions and to rely on an external, user selected GIS for image display, as well as for additional data manipulation and raster algebra operations. Within this general framework, the digital elevation data is processed in TOPAZ by a system of interdependent computational programs. The analytical operations performed by these programs achieve three broad functions:

(1) elevation data pre-processing, (2) hydrographic segmentation, and (3) topographic parameterization.

4.2.2. Elevation Data Pre-processing

DEMs commonly contain localized depressions and flat surfaces, most of which are artifacts of the horizontal and vertical DEM resolution, DEM generation method, and elevation data noise. These features are problematic for the downslope flow routing concept on which many DEM processing models, including TOPAZ, are based. Depressions are sinks at the bottom of which drainage terminates, and flat surfaces have indeterminate drainage. Therefore, TOPAZ pre-processes the input DEM to rectify these features and allow the unambiguous determination of the drainage over the entire digital landscape. Rectifications made during DEM pre-processing are strictly limited to cells of depressions and flat surfaces so as to minimize the impact on the overall information content of the elevation data.

Among the innovative capabilities provided by TOPAZ is the ability to distinguish between two types of depressions: sink-depressions and impoundment-depressions. Sink-depressions are caused by a group of raster cells at lower elevation than the surrounding landscape, and impoundment-depressions are caused by a narrow band of raster cells of higher elevation across drainage paths, similar to an obstruction or dam across a stream. In the latter situations, TOPAZ can lower selected DEM elevation values to simulate breaching of the obstruction or dam across the drainage path. This removes or reduces the size of the impoundment-depression. Any remaining depression after the breaching is considered to be a sink-depression. Sink-depressions are treated in the conventional manner by raising the elevations within the depression to the elevation of its lowest (breached) overflow (Martz and Garbrecht, 1998).

The flat surfaces produced by this depression-filling, as well as those inherent to the DEM, such as level valley floors or plateaus at drainage divides, require further rectification to ensure unambiguous downslope drainage at every location in the DEM. In TOPAZ, this is achieved through a relief imposition algorithm which takes into consideration the rising and falling topography surrounding the flat surfaces to generate a realistic, topographically consistent and convergent drainage over those surfaces. Arbitrary drainage direction assignment is minimized because the topography surrounding the flat surface controls the relief imposition and drainage determination. The DEM that has been rectified for depressions and flat surfaces is the basis for all subsequent topographic evaluations (Garbrecht and Martz, 1997a).

4.2.3. Hydrographic Segmentation

Hydrographic segmentation identifies the channel network, the upstream and lateral sub-catchments contributing flow to each channel link in that network and corresponding drainage divides. The drainage over the digital landscape is first determined as the steepest downslope path from each raster cell to one of its 8 adjacent cells. The upstream drainage area at each raster cell is then determined using the downslope flow routing concept, and the channel network is defined as those cells with an upstream drainage area greater than a user-defined critical source area (CSA) value. The critical source area is the drainage area at which a permanent channel

begins. The network identified in this way is a fully- connected, convergent and uni-directional downslope channel network.

One of several innovations in TOPAZ is the capability to generate a hydrographic segmentation and channel network with spatially varying characteristics; that is, the network structure, drainage density and sub-catchments properties can be different in different parts of the watershed. This capability is used to account for spatial variation in hydrologic controls such as geology, soil type, vegetation and/or climate. TOPAZ can also prune very short, and likely spurious, exterior channel links from the generated channel network.

The above capabilities allow the generation of channel networks of different density and resolution to meet the scale, needs and purpose of a particular application. For example, the same drainage network can look quite different when examined on topographic maps of different scales. This different network density/resolution can be reproduced by TOPAZ by either generating all large and small channels within the landscape, only the largest channels, or a network between these two extremes. Once the channel network has been fully defined, it is further processed to determine the Strahler order of each channel link and to assign an identification number to each network node and channel link (Garbrecht and Martz, 1997b). These identification numbers are used to determine the optimal routing sequence for cascade-type flow routing through the channel network (Garbrecht, 1988).

Sub-catchments represent the direct contributing drainage areas of the left and right side of each channel link, and of the source node or upstream end of each exterior link or 1st order channel. Sub-catchments and corresponding divides are determined from the previously defined drainage pattern and channel network. Also, subcatchment identification numbers based on network node and channel link identification numbers are assigned to provide the topological relationship between network nodes, channel links and sub-catchments.

4.2.4 Topographic Parameterization

Topographic parameterization involves measuring a variety of properties and parameters of the DEM raster and of the derived channel network, channel links and sub-catchments. Spatial parameters, such as rectified elevations, landscape slope and aspect, drainage pattern, channel network and subcatchment boundaries, are generally stored in raster format and are available for visual display using an external GIS. On the other hand, parameters that describe specific features of the landscape, such as the geometry of a channel link or subcatchment, are stored in tabular format. Examples of channel network parameters include number of channel links, total channel length, subcatchment area, drainage density and network composition parameters. Examples of channel link parameters include link length, slope, elevation, upstream and lateral drainage area, and topologic connectivity information. Examples of subcatchment parameters include representative drainage area, length, slope, aspect distribution and overland flow distance. A complete list of computed properties and parameters can be found in the documentation of individual TOPAZ programs.

Raster derived channel networks often contain junction nodes with more than two inflows. Such junction nodes are referred to as complex junction nodes. Complex junction nodes very seldom occur in nature. Tributaries joining a main stem generally are spaced along the main stem, though the spacing between junctions can occasionally be small. Complex junctions in generated raster channel networks can be common. They are the result of a low horizontal DEM resolution that cannot resolve the spacing between two or more consecutive tributary junctions, thus lumping multiple junctions together into a single cell. A TOPAZ feature allows the decomposition of complex junction nodes into a sequence of simple junction nodes (only two inflows per junction) at a sub-raster resolution. The resulting channel network is called a binary channel network because it always has two upstream inflows per junction. The binary channel network is believed to be a better approximation of natural channel networks because it overcomes the effects of systematic lumping due to limited raster resolution. At the user's choice, properties and parameters of the binary channel network and corresponding channel links and sub-catchments are computed and tabulated in a manner similar to that for the raster channel network, channel links and sub-catchments.

In addition to computing the parameters of each channel link and subcatchment, TOPAZ evaluates the mean and standard deviation of these parameters over the entire channel network, as well as by Strahler order. Topaz also computes the drainage network composition parameters. The entire statistical evaluation is performed for both the raster and binary channel networks.

4.2.5. Assumptions and Limitations

General assumptions and limitations of the D8 method, the downslope flow routing concept, and the CSA concept, as described in O'Callaghan and Mark (1984), Douglas (1986), Fairfield and Leymarie (1991), and Costa-Cabral and Burges (1994), apply. Also applicable are assumptions and limitations pertaining to DEM resolution (vertical and horizontal) and finite (raster) representation of landscape elevations. Of particular significance for TOPAZ are the following four assumptions/limitations:

a) the DEM must be of sufficient vertical and horizontal resolution to allow the identification and parameterization of the channel network, sub-catchments and other landscape features of relevance;

b) local drainage and flow direction can adequately be defined by 8 directions: 4 diagonal to and 4 in the principle raster directions;

c) upstream drainage areas and drainage paths are adequately described by downstream flow routing from one cell spilling onto another adjacent cell in the direction of steepest descent;

d) the channel network is adequately described by all cells that have an upstream drainage area above a user specified threshold drainage area, the CSA parameter;

e) representative values of distributed subcatchment properties are quantified based on models that define the reduction of distributed values of the properties into single representative values.

The above five assumptions/limitations do not inhibit the numerical processing of DEMs by software TOPAZ; they only impact the quality and usefulness of the TOPAZ produced data. The major implications of the assumptions are discussed in the following:

Assumption a):

Landscape features of relevance must be several times the size of a raster cell to be uniquely identifiable and lend themselves to parameterization. For example, DEM elevation cannot represent thalweg elevation of incised channels that are narrower that the horizontal DEM resolution. As a result, computed drainage reflects general terrain disposition and not necessarily unresolved channel paths, unless both happen to coincide. Also, the geometric characteristics of a subcatchment cannot be accurately estimated if the subcatchment size is small and the effects of the finite raster representation significantly impacts the geometric measure under consideration.

Assumption b):

The drainage direction at a single cell can be in error by a much as 22.5 degrees. However, in dissected landscapes with convergent drainage patterns, the general drainage direction over a distance of several cells is relatively well reproduced because drainage paths are defined by topography and not by flow directions at a single cell. Drainage direction for plane, undissected hillslopes are the most susceptible to larger approximation errors.

Assumption c):

The drainage over the digital landscape is only suitable for flow analysis using forward-marching routing schemes (i.e. kinematic cascade approach), and runoff conditions without significant backwater or tidal effects. Assumption c) also allows for only one downstream path out of each cell. Therefore, divergent and braided drainage patterns cannot be modelled.

Assumption d):

The critical source area (CSA) defines the beginning of source channels (1st order channels). However, the latter often display random and systematic variations due to spatial variations in topography, soil, geology and vegetation, among others. The CSA concept cannot account for random variations. However, systematic spatial variations can be modelled in TOPAZ by use of a spatially variable CSA parameter.

Assumption e):

For a particular distributed subcatchment property there can exist several different representative values depending on the model selected for reducing the distributed values of the property into a representative value. The user must select the model that is consistent and valid for his/her particular application. The user should also be aware of the magnitude of the difference in representative values due to alternative property reduction models.

An additional assumption is that depressions and flat surfaces in the digital landscape are spurious and can be rectified to allow an unambiguous determination of downslope drainage (assumption c). Therefore, landscape drainage properties associated with true depressions (or lakes) at the bottom of which downslope drainage terminates cannot be generated directly.

As a result of assumptions a), b) and c), the landscape under consideration must be dissected by channels and display sufficient relief to define downstream flow paths. Also, the DEM must be of sufficient resolution to adequately define these drainage features. In general, the data produced by TOPAZ adequately represents most natural landscapes given sufficient DEM resolution. Man made drainage features in natural landscapes can be evaluated if they are incorporated into the DEM elevations.

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